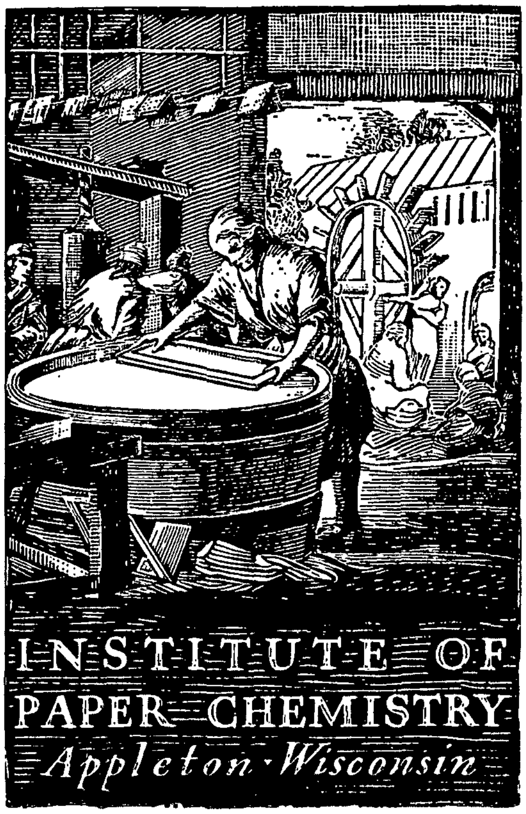

BARK AND WOOD PROPERTIES OF PULPWOOD SPECIES AS RELATED TO SEPARATION AND SEGREGATION OF CHIP/BARK MIXTURES

Project 3212

Report Eleven
A Summary Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

June 23, 1978

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

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SUMMARY

Bark morphology and bark strength properties were examined for 42 pulpwood species. Hardwood barks exhibited greater variability in both morphology and strength characteristics than conifer barks. Percent fibers, percent sclereids and inner bark strength turned out to be parameters useful in estimating wood/bark adhesion and reaction to hammermilling.

Bark specific gravity varied from 0.72 for shagbark hickory to 0.31 for eastern cottonwood. Hardwood barks tend to be either similar or higher in specific gravity than conifer barks. Conifer barks were generally similar or lower in specific gravity than associated sapwood. No consistent relationship was evident between the specific gravity of hardwood bark and that of the wood. This lack of a consistent relationship for hardwood and the discovery that for many conifers there was little difference between the specific gravity of the bark and wood, resulted in water and air flotation procedures being of very limited usefulness.

Alcohol-benzene extractives were from three to eight times as great in the bark as in the wood. Levels in the bark varied from 6.0% for red maple to 25.4% for eastern larch. Most conifer barks had higher levels of extractives than did the hardwoods. Red, slash, loblolly, shortleaf, longleaf and Virginia pine were exceptions with levels from only 5.8 to 8.8%. Despite relatively high extractive levels in a number of species, pitch problems are not expected to be serious unless, as a result of screening procedures, higher-than-normal levels of bark are concentrated in certain fractions prior to pulping.

The barks of 42 species were evaluated for the presence of fiber or fiber-like structures by both microscopic examination and a simulated kraft cooking procedure. Hardwood barks, with the exception of sycamore, white birch and red alder, had varying levels of fiberlike structures. Black willow, white ash and shagbark hickory were the species with the greatest amount of usable fiber (15-21%). Most of the conifers investigated contained little or no usable fiber with the exception of Douglas-fir with 5% and western larch with 1% usable fiber. A number of hardwood species were investigated that had useful levels of bark fiber, had few or no sclereids and could, it appears, be best utilized by pulping the bark right along with the wood.

Growing season wood/bark adhesion was very similar for all species tested and the failure zone was consistently located in the cambium zone or in the newly-formed nonlignified xylem cells just outside the cambium zone. Dormant season wood/bark adhesion varied greatly from species to species, usually being higher for hardwoods than conifers. High hardwood dormant season wood/bark adhesion was associated with the presence of fiber in the inner bark. Sclereids in the inner bark resulted in decreased dormant season wood/bark adhesion. Multiple regression equations were developed that used inner bark strength and wood toughness to predict wood/bark adhesion. The developed prediction equations accounted for 72% of the variation encountered in wood/bark adhesion. Inner bark strength turned out to be the parameter most useful in predicting conifer and hardwood wood/bark adhesion.

Weighted average bark strength of hardwoods was positively correlated with percent fibers and negatively correlated with percent sclereids in the inner bark. Conifer bark strength was not correlated with either of the above two morphological characteristics but, as indicated above, inner bark strength was useful in predicting conifer wood/bark adhesion.

Hardwood bark toughness varied from 0.79 for shagbark hickory to 0.09 for red alder and could be predicted, using multiple regression techniques, from bark specific gravity, percent fibers and percent sclereids. Similarly, conifer bark toughness could be predicted from bark specific gravity and percent fibers. Of considerable practical interest was the finding that bark toughness was consistently less than wood toughness. This suggests the possibility of the development of some type of mechanical action that takes advantage of this toughness difference as an approach to the segregation of wood/bark mixtures.

The "reaction of conifer and hardwood barks to hammermilling" investigates the use of a hammermilling-like mechanical action to break up the bark and allow segregation by screening. Bark removal for hardwood varied from 11% for shagbark hickory to 48% for red alder. Conifer bark removal varied from 23% for white spruce to 44% for balsam fir. Bark removal for both hardwoods and conifers was increased by the presence of sclereids and decreased when fiber was present. Overall, the use of hammermilling as the first step in a dry wood/bark segregation procedure continues to look promising. To successfully reduce bark to appropriate levels will require an improved mechanical treatment method and better screening procedures.

Bark fuel values, when expressed on an oven dry basis, were negatively correlated with the ash content and correlated positively with the level of alcohol-benzene extractives. All 18 conifers investigated had fuel values greater than 8,500 Btu's per oven dry pound. Seven of the hardwoods evaluated had values greater than 8,500 and the remaining 17 species varied from 6,773 to 8,453 Btu's per o.d. pound. Most hardwood barks were higher in specific gravity than conifer bark and when fuel values were expressed on a per cubic foot basis had higher fuel values than the conifers.

Ash content, including calcium, was found to be 10 to 15 times as great in the bark as in the wood. Use of barky whole-tree chips, particularly chips from several of the major hardwood species, can be expected to increase recovery systems evaporator scaling problems, and should be a factor given appropriate consideration when evaluating the need for debarking procedures.

INTRODUCTION

Project 3212 was established as a group project in the spring of 1974. The objective of the project was to characterize the bark properties of the principal pulpwood species of North America. The original list of cooperating companies included Abitibi Paper Company, Ltd.; Blandin Paper Company; The Mead Corporation; The Procter and Gamble Company; Scott Paper Company and Weyerhaeuser Company. IPC member company interest in bark characteristics increased greatly during the next year and, as a result, the project was switched to a funded project in July of 1975. This increased interest apparently resulted from the realization by many companies that at least a part of their future fiber supply would be provided by short-rotation forestry and through the utilization of logging residue. Both approaches mean greater utilization of whole-tree type chips, and the potential of increased bark and dirt problems.

A number of economic and social changes have occurred since the start of the program which have resulted in the modification of bark tolerance levels, wood loss standards, and in changes in what can now be considered as acceptable procedures for handling wood/bark mixtures. The social changes have taken the form of pressures by society to improve the environment and the principal economic change has been rapidly increasing energy costs. Pressures to reduce water use, and the need and cost of treating waste water, has resulted in greater buildup of contaminants under "closed" mill conditions and reduced interest in water flotation as an approach to wood/bark segregation. Use of whole-tree chips, before the magnitude of associated bark problems was fully realized, resulted in further revision of the standards for acceptable bark levels and wood losses. Presently, energy costs, fiber supply and fiber raw material requirements are the key factors in the whole-tree harvesting and wood/bark segregation picture. Delivery of a quality finished product to the consumer at the lowest energy output requires consideration of harvesting, transporting, chipping, pulping, cleaning, beating, chemical recovery, equipment wear and energy recovery costs. Consideration must also be given to energy independence. Bark and low-quality chips, for example, have a considerable fuel value and, if handled and segregated by a dry process, could make a major contribution to the industry's overall energy requirements.

Because of the great variation in wood and bark properties of pulpwood species, the basic approach has been that a single best solution to the bark problem could not be developed. With this in mind, it appeared the most useful service the Institute could perform would be to provide interested companies with a concise package of data on each of the more important pulpwood species, and in this way better define the problem. This, we felt, would enable resource managers, once the diversity of species being utilized was known, to work out an acceptable "best solution" for a specific mill situation.

With the above objectives in mind, a program was established to systematically characterize the most important North American pulpwood species. Company input was used to select those species to be investigated and over a four-year period a total of 42 species, 18 conifers and 24 hardwoods, were characterized. The report that follows has the objective of summarizing the data obtained during this four-year period in a series of tables that allow us to review with you the relationships that exist between bark morphology, density, strength, fuel value and pulping potential. A number of these relationships promise to enable the extension of the results to species that have not been studied. Appendix Table XXXVI lists the species covered in each report.

EXPERIMENTAL PROCEDURES

The experimental procedures employed have, as much as possible, been standardized and the same methods used for each tree species. To avoid repeating the descriptions involved, the information has been consolidated into a single section and is discussed below.

TREE SIZE AND SAMPLE LOCATION

Budget limitations made it imperative that tree size and sample location be standardized. Cooperating agencies and the Institute's field sampling crew were asked to sample trees 7 to 9 inches in diameter at breast height (4-1/2 feet). The wood/bark adhesion and bark strength samples were taken at or near breast height. In addition to breast high samples, most trees were cut and an additional 18 to 36-inch bolt was obtained from the area just below the breast high sample. The latter sample was used for wood and bark toughness, bark strength, wood and bark specific gravity, wood and bark basic density, and for water flotation studies.

SAMPLING PROCEDURES

Two different sampling procedures were used for obtaining undisturbed wood/bark adhesion samples. The simplest procedure involved merely cutting the tree and carefully removing a 5 to 6-inch bolt at breast height. The second, and slightly more complicated, procedure is demonstrated in Fig. 1. Using a chain saw, a series of horizontal and vertical cuts allows the removal of three wedge-shaped samples. The more complicated procedure was used when sample size and weight were factors in air freight shipment for speedy processing. For all wood/bark adhesion and bark strength measurements, the samples were kept cool during shipment and measurements were made within 72 hours after collection. No special handling procedures were employed for the wood and bark samples used in making the other tests

Figure 1. Satisfactory Test Samples were Obtained from Standing Trees Using a Small Chain Saw. Illustrated are the Steps Involved, Including: (A) Making a Series of Four Parallel Horizontal Cuts About Four Inches Apart with the End of the Chain Saw, (B) Making Two Parallel Vertical Cuts, Connecting the Horizontal Cuts, and on an Angle that Produced a Wedge-shaped Sample, (C) Gently Lifting out the Sample with a Hammer

other than the procedures used to adjust the samples to a constant moisture prior to testing. This technique involves moistening the samples and then allowing the test specimens to equilibrate to a constant moisture content (approximately 20%) by placing the material in a constant temperature, constant humidity (50%) room for a minimum of 10 days or adjusting to 100% moisture content by adding an appropriate amount of water to the samples and equilibrating in polyethylene bags in the refrigerator for a minimum of 10 days.

PREPARATION OF SIMULATED CHIPS

To facilitate comparisons between species and to speed processing and handling in those tests where wood and bark chips were required, standard-sized simulated chips were used. For several tests, the standard-sized chips were further subdivided and, where this occurred, this was so stated in the procedure. The standard chips were 1-inch long (parallel to the grain), 0.6-inch wide and 0.2-inch thick and were prepared by subdividing a 1-inch-thick disk. The procedure involves cutting a 6/10-inch wide strip across the disk, starting at one edge and going through the middle of the disk. A guillotine cutter was used to further subdivide strips into heartwood, sapwood, and bark chips. Additional bark chip samples were prepared by making band saw cuts 6/10-inch apart around the margin of the disk and removing the bark chips with a chisel.

WOOD/BARK ADHESION MEASUREMENTS

Most early investigations into wood/bark adhesion used tests designed for bolts or standing trees. These were judged to be unsatisfactory for examining changes in chip samples. The wood/bark measurement technique used was developed in a previous group project (Project 2929) and measures shear parallel to the grain on a small (3/16-inch x 3/16-inch x 1 1/4-inch) specially prepared test sample.

The failure zone was controlled by making cuts in the test specimen from the bark side and the wood side with the distance between the cut being 1/8-inch and the cuts overlapping by 0.010 inch in the cambium zone region. The surface area of the wood/bark interface being tested was 0.0234 square inch or 0.151 square centimeter. Figure 2 illustrates several of the steps used in preparing the sample prior to testing in the Instron tester.

For testing, the specimens were mounted in an Instron testing machine as shown in Fig. 2D. The clamping jaws were 0.02-inch wide and were separated by a distance of 0.75 inch. Specimens were strained at a rate of 0.2-inch per minute. Four to nine specimens were tested for each tree on each testing date. Each specimen, after testing, was examined and the type of failure noted. Representative specimens of each species were immersed in ethyl alcohol immediately after testing for later morphological examination.

One important limitation of the IPC procedure for measuring wood/bark adhesion (and a limitation for all procedures presently being employed) is that, during the dormant season, when failure occurs in the bark, the magnitude of the test value is dependent upon the strength of the inner bark of the species involved. All that can be said about the values obtained during this period is that "adhesion in the cambium zone and in the bark and wood elements immediately adjacent to the cambium zone is in excess of the values obtained." The dormant season test values do, however, provide an indication of the difficulties that can be expected in bark removal during the dormant season.

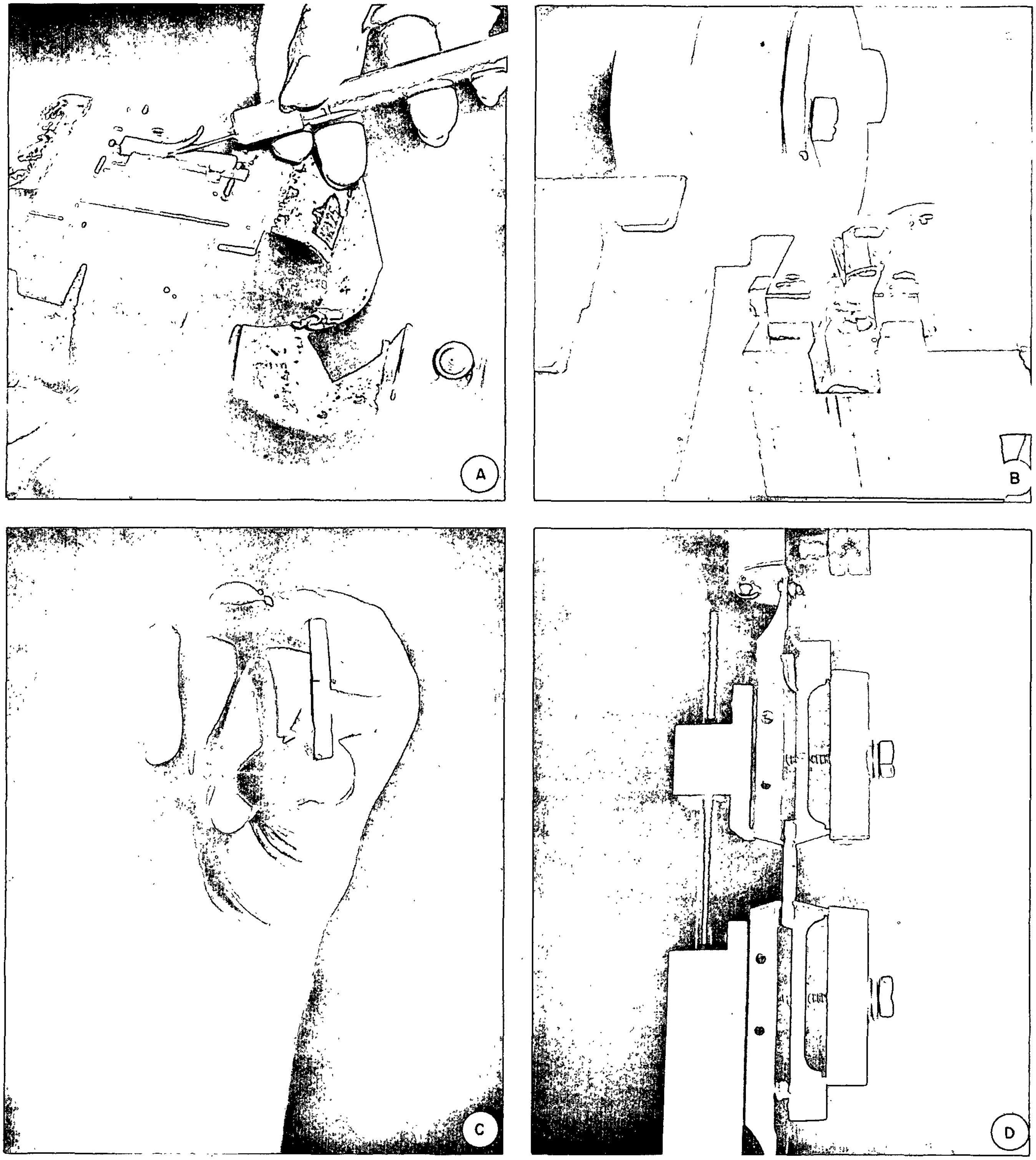

Figure 2. Small Test Samples Suitable for use in the Instron Tester were Prepared by Cutting the Sample to Approximate Size on the Band Saw. The Samples were then: (A) Shaved to the Exact Dimensions, (B) Cuts Made Through the Bark and Wood to Cambium, (C) Removed from the Jig Used in Holding the Sample During Cutting, (D) Tested for Adhesion (Shear Parallel to Grain) in the Instron Tester

BARK STRENGTH MEASUREMENTS

Bark strength measurements were made using essentially the same procedures as used in measuring wood/bark adhesion. Test specimens were prepared as described for the wood/bark adhesion test with the exception that, when inner bark strength was being tested, the two cuts made from opposite sides of the test specimen were prepared so as to overlap in the inner bark zone. When testing the strength of the outer bark, the cuts were so located to overlap in the outer bark region. The location of the overlap of the cut was the factor controlling the zone of failure. The strength measured was shear parallel to the grain.

BARK TOUGHNESS MEASUREMENTS*

The brittleness or toughness of bark is believed to be important because it is expected to be related to the ease with which bark can be broken into small particles by hammermilling or similar procedures. The ASTM toughness test for wood is not suitable for use with small bark samples. After investigating 3 different methods of promoting rupture, the energy required to rupture a small bark or wood sample by bending with a force parallel to the diameter of the tree was selected. The specimens for the bending tests were cut to a width of 0.455 cm and long enough to permit a test span of 1.92 cm. The thickness of the specimens varied depending upon the bark thickness of the species being tested. The specimens were tested using a center-load beam test. Both the supports and loading ram were 1/8-inch diameter steel pins. The specimens were tested at a rate of 0.254 cm/min. The properties evaluated from the load-deformation curves were unit stress $\underline{S}$, Young's modulus $\underline{E}$, and elastic energy $\underline{U}$:

*Toughness test developed by Roger Van Eperen and W. A. Wink of the IPC Paper Evaluation Group.

$$S = PL/4 \times c/I = 1.5\ PL/bd^2 \qquad (1)^*$$

$$E = PL^3/4ybd^3 \qquad (2)^*$$

$$U = S^2/18E \qquad (3)^*$$

where $\underline{P}$ = force at proportional limit

$\underline{L}$ = beam length

$\underline{c}$ = distance of outer fiber from neutral axis

$\underline{I}$ = rectangular moment of inertia about the neutral axis

$\underline{b}$ = beam width

$\underline{d}$ = beam thickness

$\underline{y}$ = beam deflection at $\underline{P}$.

The elastic energy ($\underline{U}$) for inner bark, outer bark, and wood is the value reported and is reported in terms of kg cm/cm^2. Because, during preliminary testing and development of the method, bark toughness (elastic energy) was found to decrease as the moisture content of the sample increased, all samples were tested after equilibrating at 50% RH for a minimum of 10 days (20% moisture, o.d. basis). Both bark strength and bark toughness will be examined and attempts made to relate the data to simulated hammermilling tests.

HAMMERMILLING TESTS

A hammermilling test procedure was developed for use with 1/2-sized (1-inch x 3/10-inch x 2/10-inch) simulated bark and wood chips. The objective of the test was to relate bark strength and bark toughness to a hammermilling type of action. A standard "Micro Pulverizer"** was modified to reduce the severity of the

*From Marks Mechanical Engineers Handbook, 6th edition, 1958.
**Pulverizing Machinery Company, Roselle Park, NJ.

action. Modifications included reducing the electric motor rpm from 3500 to 1725, removing four of the six hinged hammers, rounding the edges of the remaining two hammers to decrease the cutting action and increase the clearance between the hammers and the pulverizing chamber to 0.35 inch. A fine mesh herringbone type of screen was replaced with a screen with holes of 0.5-inch diameter. The air intake on the Micro Pulverizer was set at full open in order to move the sample through the pulverizer as rapidly as possible.

Samples were moistened and then equilibrated in a 50% RH room for 10 days prior to testing. The chips were fed through one at a time and the resulting material caught in a cloth bag. After all the chips had been fed through, the bag was removed and emptied on a series of soil screens. The screens include 5-mesh, 10-mesh, 14-mesh, 20-mesh, 28-mesh, and fines. Material on each screen was weighed and a percentage of the total calculated. This procedure was followed for both bark and wood chips of each species tested. In addition, each bark fraction was characterized as to how much inner and outer bark it contained.

SPECIFIC GRAVITY, BASIC DENSITY, AND MOISTURE CONTENT MEASUREMENTS

Specific gravity of small bark and wood samples was determined using a water displacement technique that is a modification of the TAPPI Standard Method, T 18 m-53. The sample specimens of wood were soaked for approximately 24 hours and the bark for a minimum of two hours prior to being processed in order to be certain that a maximum green volume was being measured. Results were expressed in terms of dry weight/green volume.

The basic density of small wood and bark samples at various moisture contents was determined using the pycnometer method with the chemical, heptane, employed as the displacement medium. The test specimens having various moisture contents were prepared by placing the required number of chips in small tightly covered jars containing varying amounts of water. Chips were allowed to equilibrate for a minimum of 10 days and the basic density measurements were made following equilibration. First, the density of the heptane was determined using a 25-ml pycnometer [(weight filled pycnometer — weight of empty pycnometer)/25].

When measuring the basic density of the moist chips, replicated determinations were made by subdividing the standard-sized chips into two or three pieces depending upon the number in each jar. One piece from each chip was blotted free of excess moisture and the two (or three) pieces making up the replication were weighed to get a wet weight. However, the inner and outer bark samples, and sometimes the total bark samples, were not subdivided because of the thinness and/or brittleness of the pieces. The chips from a particular replication were then placed in the pycnometer, heptane was added and the weight obtained on an analytical balance for the pycnometer containing the heptane + the chip replication. Usually a rough weight was obtained, the pycnometer removed, more heptane added and a final weight taken. This was necessary because of the rapid evaporation of the heptane. The replication was then removed from the pycnometer and placed in an appropriately marked coin envelope.

After all the samples were taken care of in this manner, they were oven dried for 24 hours at 105°C and an ovendry weight obtained. With this information, it was possible to calculate moisture content and density. Moisture content was calculated as (wet wt.–o.d. wt.)/o.d. wt. Density was calculated as $(\underline{c}\underline{d})/[\underline{c}-(\underline{b}-\underline{a})]$

where: $\underline{a}$ = weight of pycnometer + heptane

$\underline{b}$ = weight of pycnometer + heptane + chip

$\underline{c}$ = weight of chip (wet — before being placed in heptane)

$\underline{d}$ = density of heptane.

DWELL TIME MEASUREMENTS

Dwell time was measured to determine how rapidly the bark and wood of a particular species absorbs water and sinks. Approximately 50 grams of 1/2-standard-sized chips were weighed (bark, heartwood, or sapwood) and allowed to soak for 1/2-hour in water. Chips were not allowed to soak longer because it was felt the loss of extractives might affect the dwell time. They were moved after this time and equilibrated for 10 days in a controlled humidity and temperature room (73°F, 50% RH). Containers were filled with water and allowed to come to room temperature for 24 hours prior to use. Chips were then placed in the water and the sinking chips removed after 5 minutes, 15 minutes, 1 hour, and 4 hours. The final test involved determining the ovendry weight of the fraction sinking after the various times.

A change was made in this procedure for the last ten species as follows: An appropriate amount of water was added to bring the chips to 100% moisture content (o.d. basis) and they were then equilibrated for at least ten days in polyethylene bags in the refrigerator. Before the chips were placed in the containers, a small amount was removed and actual moisture content determined. This change in procedure was made to check the flotation characteristics of the species at close to fresh moisture content.

BARK MICROPULPING PROCEDURE

Bark from breast high samples (4.5 feet) of the species involved was micropulped using the procedure of Thode, et al. (1). Cooking conditions were as follows:

Maximum temperature, °C	170
Time to maximum temperature, hours	2
Time at maximum temperature, minutes	65
Liquor analysis, g.p.l. as NaOH	40
Sulfidity, %	20
Liquor-to-wood ratio	10

As each vessel was removed from the oil bath, it was showered successively with steam, hot water and cold water. All vessels were then quenched in a container of cold water before opening. The contents of each vessel, together with rinse water to remove all chemicals and solids, were fiberized for two minutes in a Waring Blendor. The fiberized material was decanted on a sintered glass funnel and the liquid removed with a vacuum. Wash water was added and removed as required to clean the samples. An aliquot was removed, filtered on No. 1 Whatman paper and oven dried to provide yield data. The rest of the bark sample was kept in a wet state and put through a series of screens including 60-mesh, 100-mesh, 150-mesh and 200-mesh. The fractions that stayed on each screen plus the cellular elements that passed through all screens were examined for the type of cellular material they contained.

BARK AND WOOD ANATOMY

Since the anatomical features of the wood of all the species examined in this study are already well documented in Project Reports One-Ten, as well as in other texts, only the bark structure of these trees will be addressed in this summary report.

BARK DEVELOPMENT AND TREE GROWTH

Until a tree attains maturity, the enlargement of the crown and root system proceeds at a fairly rapid pace. After maturity, growth is slower, although enlargement of some parts of the crown and root system continues throughout the life of the tree. The bole gradually increases in diameter until the tree dies or is destroyed, and some species may eventually show a significant accumulation of bark tissue.

Elongation of the bole and branches and the initiation of new branches is effected by apical growing points or meristems and is termed primary growth. Tissues arising from these apical meristems are called primary tissues (xylem and phloem) and determine the fundamental form of the tree.

As a tree adds growth through the apical growing points, it must also thicken to support the crown of the tree. Responsible for this increase in stem thickness is the vascular cambium, a secondary or lateral meristem which develops between the bark and wood on older stems and roots throughout the tree. The cambium produces annually new bark and wood that is located between the old bark and wood (Fig. 3). Growth resulting from this cambium is termed secondary growth, and tissues originating from the cambium are called secondary tissues (xylem and phloem). These tissues add to the bulk of the plant, strengthen the stem and roots, and determine the ultimate form of the tree.

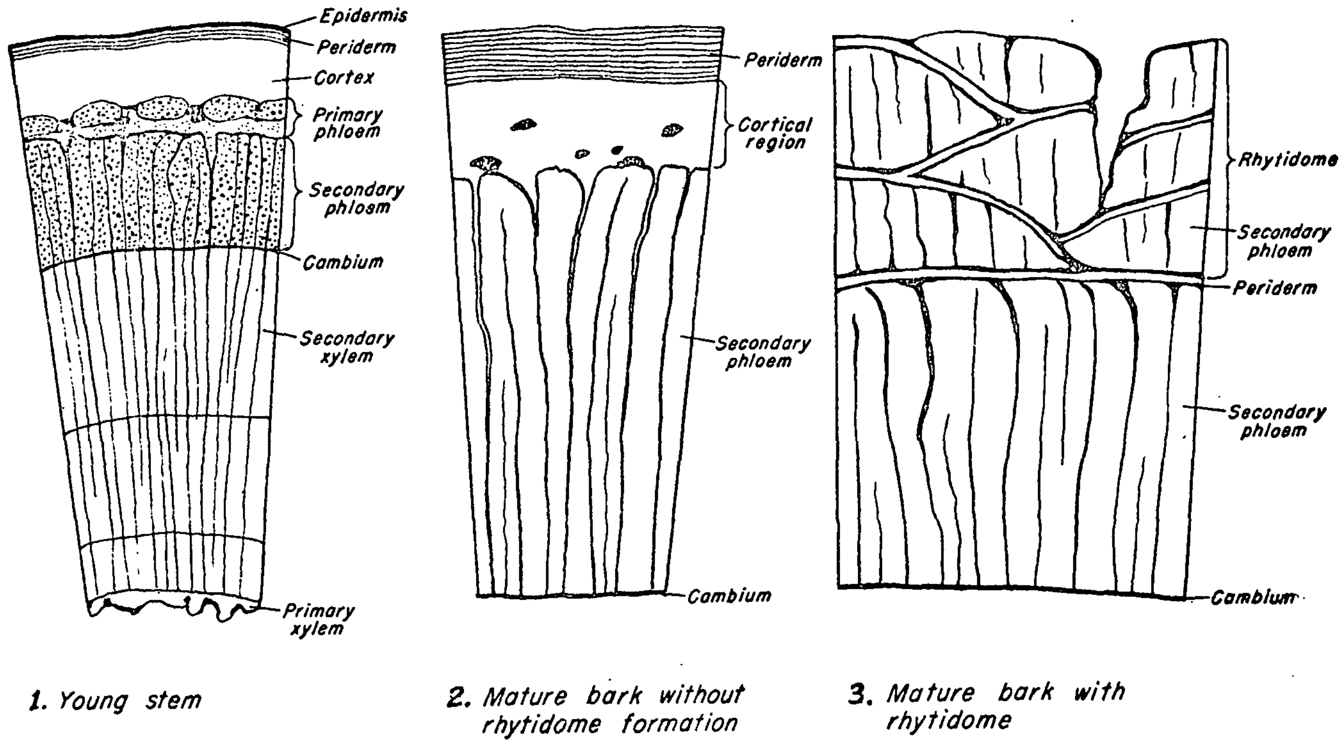

Figure 3. Drawings Showing Cross Sections of the Main Tissues in Different Types of Bark. 1. Young Branch or Stem. 2. Bark Having Persistent Cortex, such as that in the Middle-aged Balsam Fir and Quaking Aspen. 3. Mature Bark with Rhytidome Formation [from Chang (2)]

A very young stem is protected for a short time by an epidermis, which prevents loss of tree moisture but at the same time contains openings to aerate underlying tissues. Usually during the first year the epidermis is sloughed from the tree, however, only to be replaced by a more substantial tree covering — the peridermal system, which eventually gives rise to the outer bark or rhytidome. The first periderm is actually initiated underneath the epidermis, but it continues to develop and then protects the stem after the epidermis is ruptured.

A periderm (Fig. 4) consists of three distinct layers — the phellem or cork cells (to the outside), the phellogen or cork cambium, and the phelloderm cells (to the inside). The phellogen adds to both the phellem and phelloderm and behaves like the vascular cambium, becoming active during the growing season and dormant during the winter in the temperate zones.

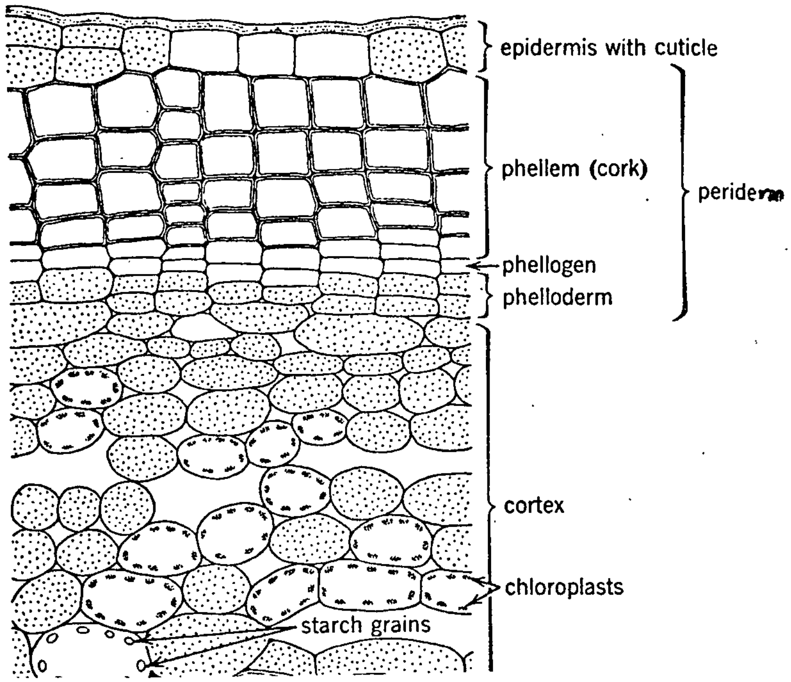

Figure 4. Initiation of the First Periderm on a Developing Woody Stem Between the Cortex and Epidermis [from Esau (3)]

During the period while the initial periderm is developing, stem thickening also proceeds from the vascular cambium. Each year, layers of new phloem (inner bark) and xylem (wood) are manufactured, all enclosed by the initial periderm. In trees with smooth outer bark, such as birch and aspen, the first-formed periderm may persist for many years. In most woody plants, however, the first-formed periderm may be shed in a few years, as it is replaced by the formation of other layers of periderm from deeper within the stem. These later-formed layers of periderm may be circumferential or may occur as overlapping short arcs (lunes). The bark tissues to the outside of these layers of periderm turn brown and die, being cut off from the vital processes of the tree. The invasion of the phloem by the later formed periderms marks the beginning of deep cork formation in the tree, and it is at this time that the outer surface of the bark may develop fissues and become roughened. In some species, the brown outer bark is fairly thin, because it weathers rapidly and is cast off. In other species, much of this dead tissue is retained, resulting in a thick and deeply fissured outer bark.

In summary, the inner bark consists of the region of secondary phloem from the vascular cambium outward to the last-formed or most recent periderm. The outer bark then refers to all tissues from the last-formed periderm to the outermost surface of the bark. The inner bark is constantly being developed by the cambium and is partly physiologically active, while tissues in the outer bark are mainly physiologically functionless. Rhytidome is a term for the scalelike outer bark and is composed of periderms and any dead secondary phloem which has been isolated by the periderms.

BARK TISSUES AND CELL TYPES

In general, tree bark carries on the same types of functions that are characteristic of the adjacent wood — namely, support, conduction, and storage. Furthermore, some of the main cell types in the bark have an analogous counterpart in the wood. These analogies are given in Table I, which also reveals the differences between softwood and hardwood barks. One feature of tree bark not found associated with the xylem or wood, however, is the periderm system or rhytidome, and that tissue was described in the previous section.

As secondary phloem is added to the stem, the cortex region is usually eventually lost. Some trees, however, maintain a cortical region between the phloem and periderm for 30-100 years. Middle-aged trees of balsam fir, red alder, white birch, and quaking aspen are examples (see Fig. 5). Sclerotic cell-wall development, extractive buildup, or crystal development may also take place in such zones.

Parenchyma cells are present in all barks, occurring as axially and radially oriented strands. The pattern tendency for axial parenchyma is toward tangential lines or narrow bands, which may be essentially continuous or interrupted locally by rays, fibers, sclereids, or other phloem cells (Fig. 6). Ray parenchyma are less consistent in their pattern of occurrence, dependent to some extent on species and distance from the cambium (age). Both ray and axial parenchyma are the most transformable cells in the bark [Chang (2)], the eventual products often being sclerotic and/or crystalliferous parenchyma, fibers, or sclereids.

TABLE I

PRINCIPAL CELL TYPES IN SOFTWOOD AND HARDWOOD BARKS

Principal Cell Function	Softwoods		Hardwoods	
	Phloem	Xylem	Phloem	Xylem
Support	Fibers Sclereids	Fibers --	Fibers Sclereids	Fibers --
Conduction	Sieve cell	Fiber	Sieve-tube member	Vessel element
Storage	Parenchyma	Parenchyma	Parenchyma	Parenchyma
Other —				
Assist in conducting cell function	Albuminous cells	--	Companion cells	--

The presence and clustering of fibers and/or sclereids is also dependent on species and phloem age. However, the general trend in many species, especially hardwoods, is for tangential banding of fibers or fiber groups, with sclereids or sclereid clusters being more common in the outer regions of the phloem (Fig. 5). Hardwood bark fibers are also commonly "gelatinous," similar to tension wood "G-fibers" in the xylem of many hardwood species (Fig. 7). Both fibers and sclereids, however, show well developed secondary walls and are lignified.

For other specific details on bark trends and patterns, one should refer to individual reports from this project or to Chang (2).

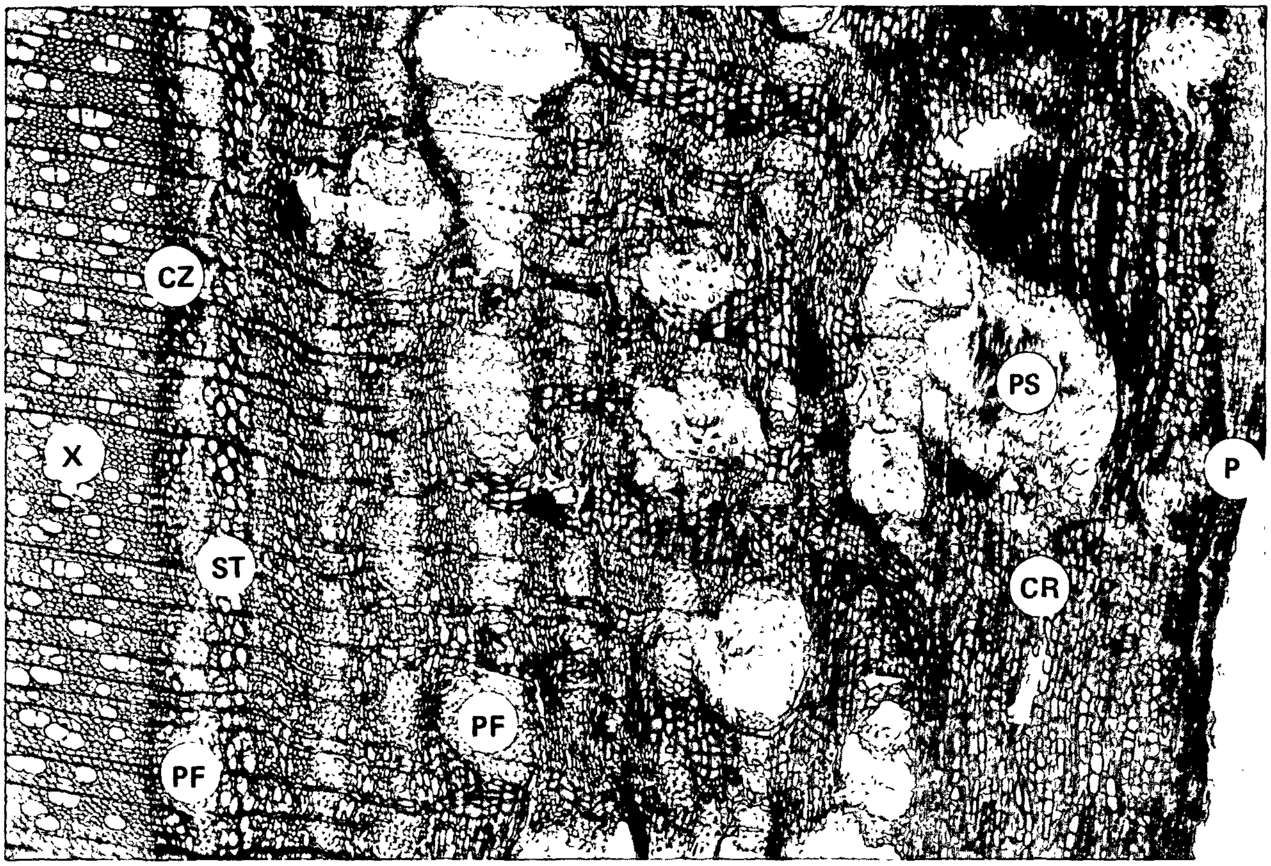

Figure 5. Cross Section of Populus tremuloides with (Left to Right) Xylem (X), Cambium Zone (CZ), Sieve Tubes (ST), Inner Bark, Cortical Region (CR), and Periderm (P). The Cortical Region and the Secondary Phloem are Merged Together by the Loosely Arranged Cortical Parenchyma, the Dilated Phloem Rays and Phloem Parenchyma Together with Scattered Groups of Sclereids (PS) and Phloem Fibers (PF). Magnification — 45X

BARK VARIABILITY — SOFTWOODS

Of the 18 coniferous tree species examined, only larch and Douglas-fir (Fig. 8) offer any value as supplemental sources of paper fiber (Table II), with larch having fibers (actually sclereidlike fibers) only in the inner bark*. In regard to possible "sclereid problems," however, if fibers are also included here, potentially all the tree types investigated except pines could serve as culprits.

*Western red-cedar, along with several other species in the Cupressaceae family, also have fiberlike elements in the bark.

The "worst" problems are likely associated with spruce, fir, hemlock (Fig. 9), and Douglas-fir. For pines, which contain no true sclerenchyma in the bark (e.g., Fig. 6, 10), the only cell types likely to contribute to paper defects are the cogwheel-shaped cork or phellem cells, which are sometimes difficult to completely separate from one another. These cork cells are often thick-walled in the pines, but also in larch and spruce. (See the "Fibrous Yield" section for further information on the incidence of these elements in pulped bark.)

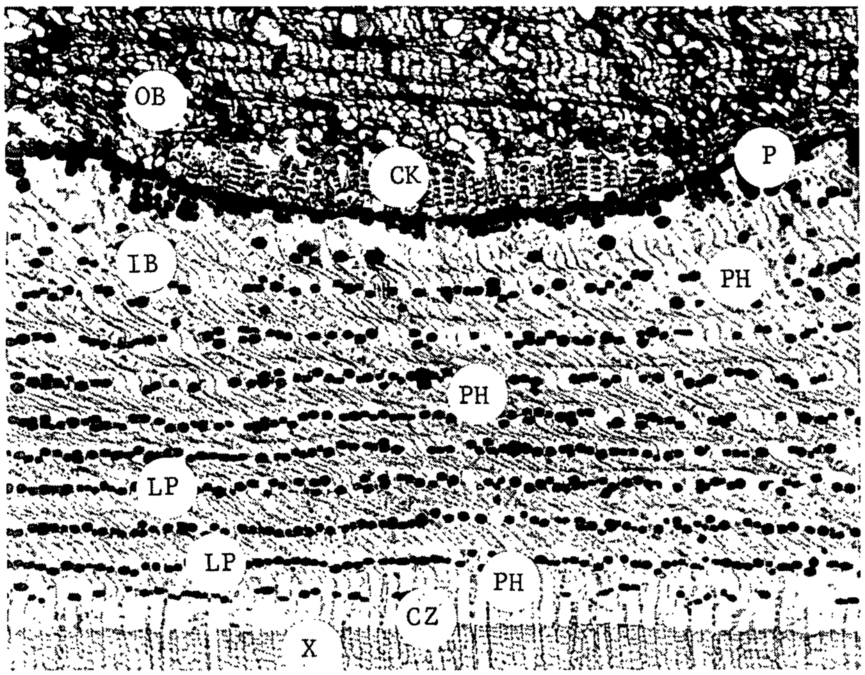

Figure 6. Cross Section of Eastern White Pine Wood and Inner and Outer Bark. Note the Distorted and Crushed Secondary Phloem (PH). Longitudinal Parenchyma (LP) are Filled with Tannin and are Aligned Tangentially. No Sclerenchyma are Present Except for Sclerotic Cork Cells (CK) in the Outer Bark (OB). Other Symbols Illustrate the Xylem (X), Cambium Zone (CZ) and a Periderm (P). Magnification — 40X

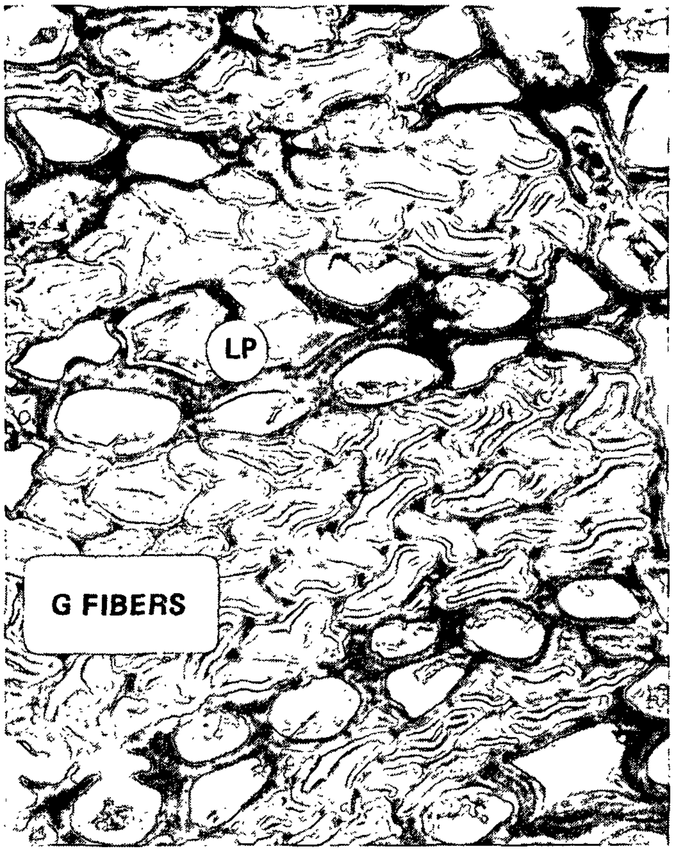

Figure 7. Illustrated is the Gelatinous Nature of the Phloem Fibers. Magnification — 750X. LP = Longitudinal Parenchyma

This study also revealed little if any structural difference in the bark of southern (hard) yellow pines; five species were examined. Furthermore, the only significant difference between hard pines and soft pines is that in the latter, the peridermal scales are shorter, more curved, and the secondary phloem tissues in the last-formed periderms mostly retain their original shape and alignment. However, horizontal resin canals in the soft pines may be larger and more frequent than in the hard pines. In general, though, there is much overlapping in the bark structure of pines, especially in closely related species [Chang (2)].

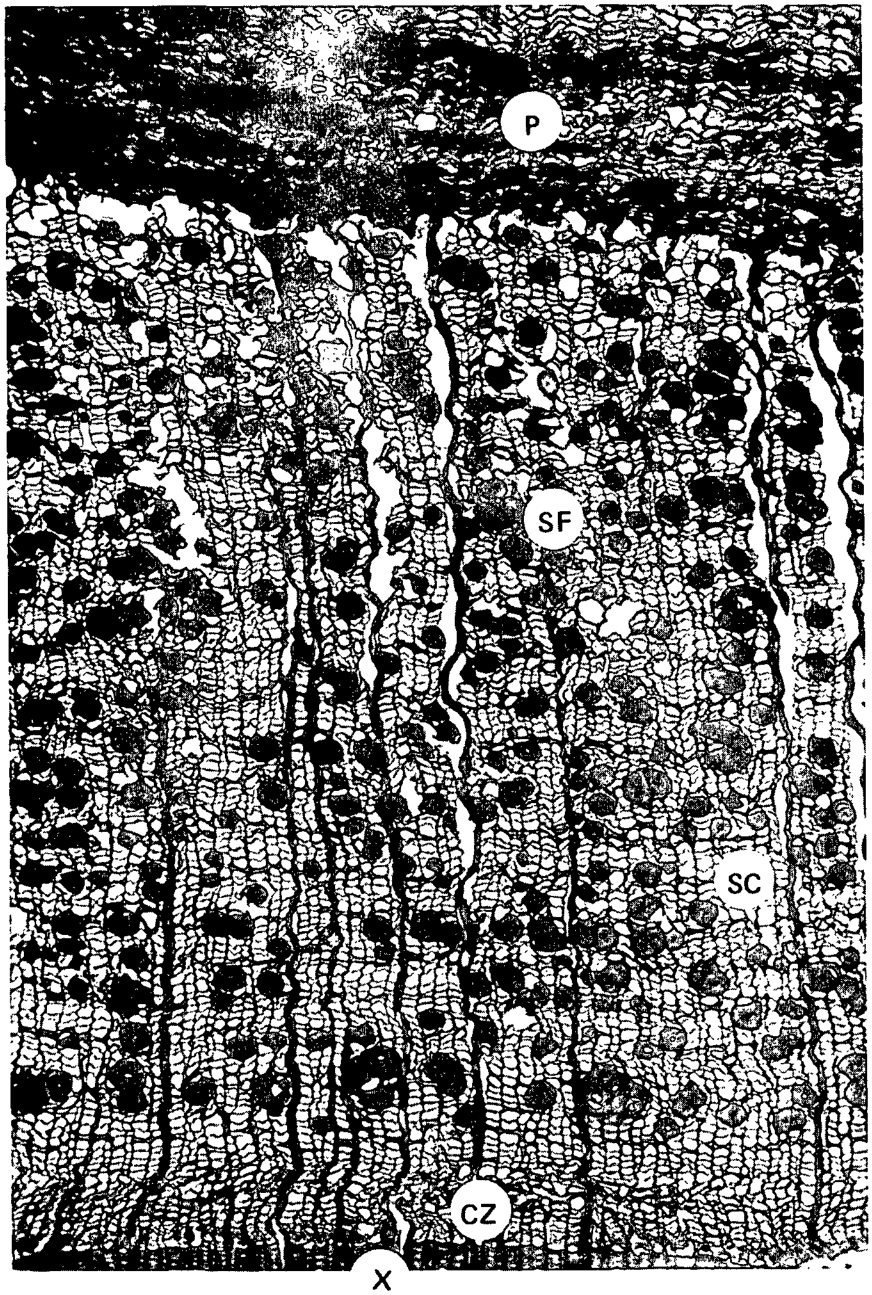

Figure 8. Cross Section of Douglas-fir Bark. Illustrated is a Small Section of the Xylem (X), the Cambium Zone (CZ), Sieve Cells (SC), Sclereidlike Fibers (SF) and Periderm (P). Shown is the Inner Bark Region Between the Cambium Zone (CZ) and the Last Formed Periderm (P), and a Single Periderm Layer. Depending on Tree Age, there are Normally Many Periderm Bands that Alternate with Areas of Isolated Secondary Phloem. Magnification — 50X

TABLE II

LOCATION OF BARK SCLERENCHYMA[a] IN CONIFEROUS PULPWOODS

Tree Type		Cell Type: Fibers IB[b]	Fibers OB[b]	Sclereids IB	Sclereids OB
Spruce	— White	--	--	x	x
	— Engelmann	--	--	--	x
	— Black	--	--	x	x
Hemlock	— Eastern	--	--	x	x
	— Western	--	--	x	x
Larch	— Western	x	--	--	--
Fir	— Balsam	--	--	x	--
Douglas-fir		x	x	x	x
Pines	— Hard	--	--	--	--[c]
	— E. white	--	--	--	--[c]

[a]True fibers or sclereids.
[b]IB — inner bark, OB — outer bark.
[c]Phellem or cork cells.

All the Pinaceae species contain resin-producing structures in the secondary phloem, while only pine, spruce, larch, and Douglas-fir have xylary resin ducts. The bark counterparts here, however, are somewhat different in form and pattern of occurrence when contrasted to normal resin ducts in the wood [Chang (2)].

Sclereids in the softwoods are often much twisted and branched, while hardwood sclereids often retain the size and shape similar to their corresponding parenchyma cells.

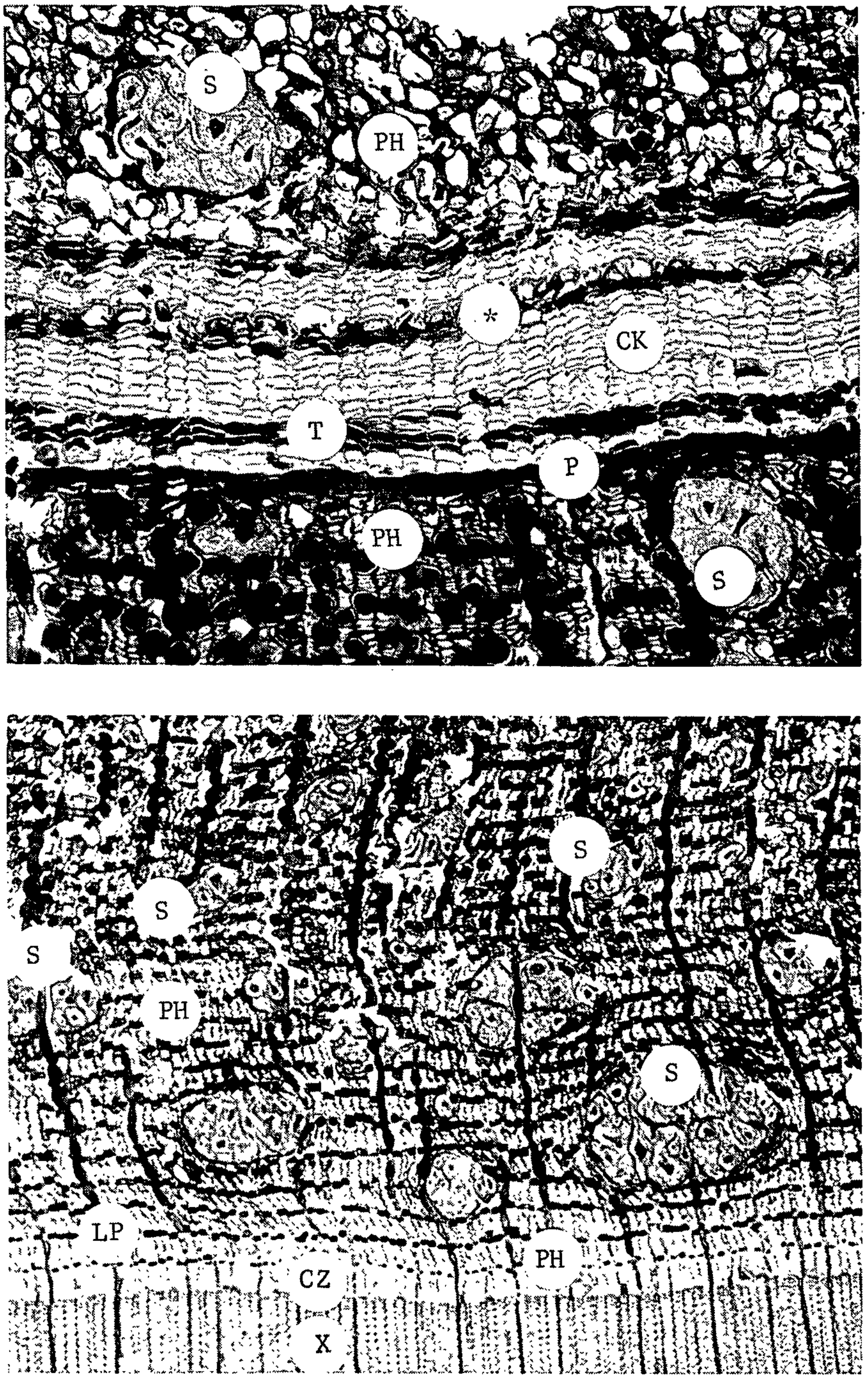

Figure 9. Cross Sections of Eastern Hemlock. Photograph on the Bottom Shows the Wood and Inner Bark with Clusters of Sclereids (S) Among Collapsing Elements of the Secondary Phloem (PH). Longitudinal Parenchyma (LP) are Evident in Tangential Bands. Also Illustrated is the Xylem (X) and Cambium Zone (CZ). The Photograph on Top Shows the Periderm System (P) with Numerous Cork Cells (CK), Isolating Regions of the Secondary Phloem (PH). Some Cork Cells are Sclerotic (*) and/or Tanniferous (T). Magnification — 75X Top, 40X Bottom

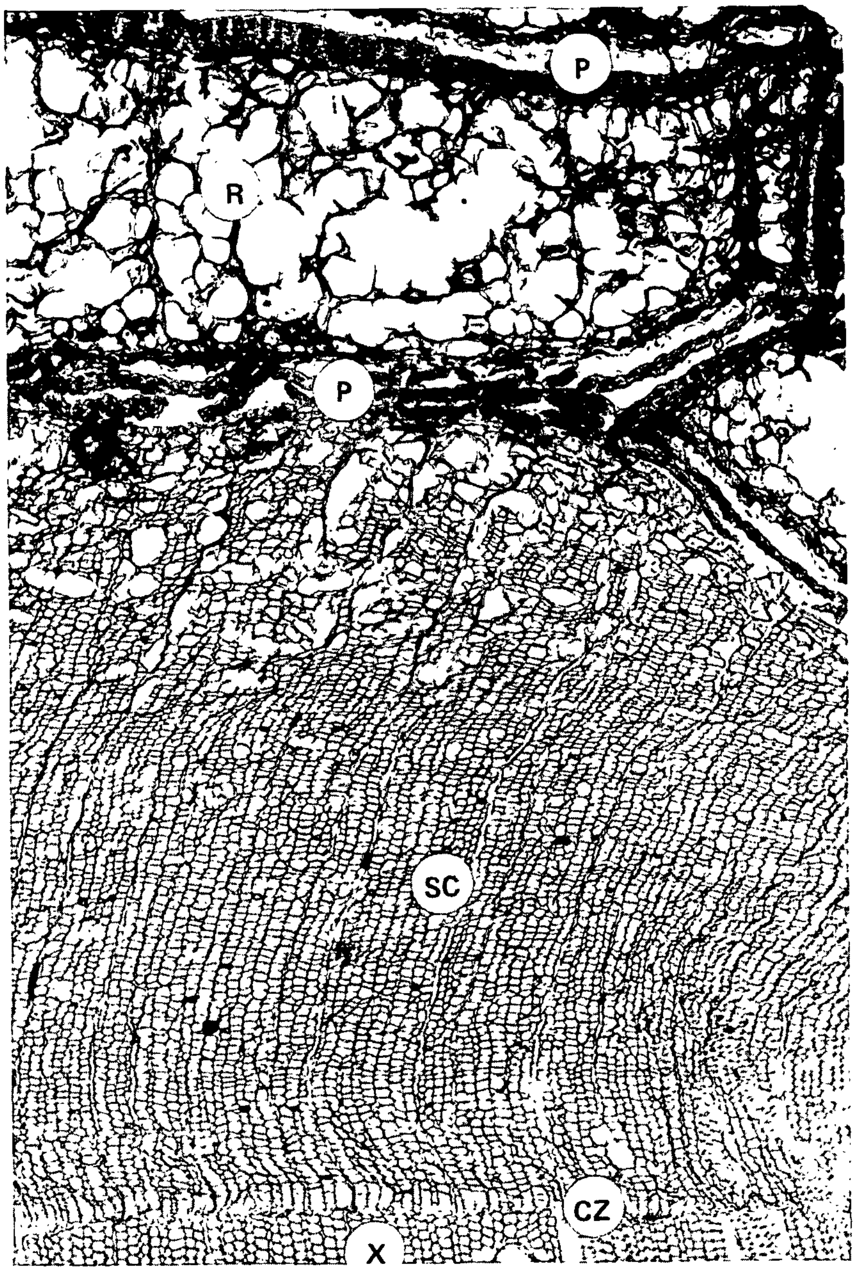

Figure 10. Illustrated is Loblolly Pine Bark. The Elements Shown Include the Xylem (X), Cambium Zone (CZ), Sieve Cells (SC), Periderm (P) Where the Short, Thick-walled Phellem Cells are Found and the Outer Bark or Rhytidome (R). The Outer Bark Consists of Alternating Bands of Periderm (P) and Isolated Secondary Phloem. Magnification — 75X

BARK VARIABILITY — HARDWOODS

From Table III it is obvious that there is significant diversity in the anatomical makeup of hardwood bark. One consistent feature, however, is the presence of true sclerenchyma, but the total proportion of these cells in the bark is apparently both species- and age-dependent.

A particular hardwood bark may contain fibers and/or sclereids, with both cell types being more commonly associated with the inner bark. Fibers were found in this zone in all species but red alder, white birch, and sycamore. Sclereids were found in all species examined except eastern cottonwood, yellow-poplar, shagbark hickory, white ash, and black willow (see Fig. 11). The "Fibrous Yield" section of this report gives further information on the amounts of fibers and sclereids in pulped bark.

Seven different species of oak were examined, including red and white oaks from both the southern and northern U.S. All contained both fibers and sclereids in their inner bark and sclereids in their outer bark (except northern red). Thus, the internal bark composition is relatively similar in commercial oaks. Noticeable distinctions can be made between red and white oak barks, but these are related to the arrangement of the phloem cells and to the form of outer bark or rhytidome [Chang (2)].

TABLE III

LOCATION OF SCLERENCHYMA[a] IN HARDWOOD BARK

Tree Type		Fibers IB[b]	Fibers OB[b]	Sclereids IB	Sclereids OB
Aspen	— Quaking	x	--	x	--
Cottonwood	— Eastern	x	--	--	--
	— Black	x	--	x	x
Maple	— Sugar	x	--	x	--
	— Silver	x	--	x	--
	— Red	x	--	x	--
Sweetgum		x	--	x	--
Birch	— White	--	--	x	--
Sycamore		--	--	x	--
Yellow-poplar		x	--	--	--
Tupelo	— Black	x	--	x	x
Ash	— White	x	--	--	--
	— Green	x	x	x	x
Beech	— American	x	--	x	x
Hickory	— Shagbark	x	--	--	--
Willow	— Black	x	x	--	--
Oak-white	— Northern	x	--	x	x
	— Southern	x	--	x	x
	— Post	x	--	x	x
Oak-red	— Northern	x	--	x	--
	— Southern	x	--	x	x
	— Black	x	--	x	x
	— Pin	x	--	x	x
Alder	— Red	--	--	x	--

[a]True fibers or sclereids.
[b]IB — inner bark, OB — outer bark.

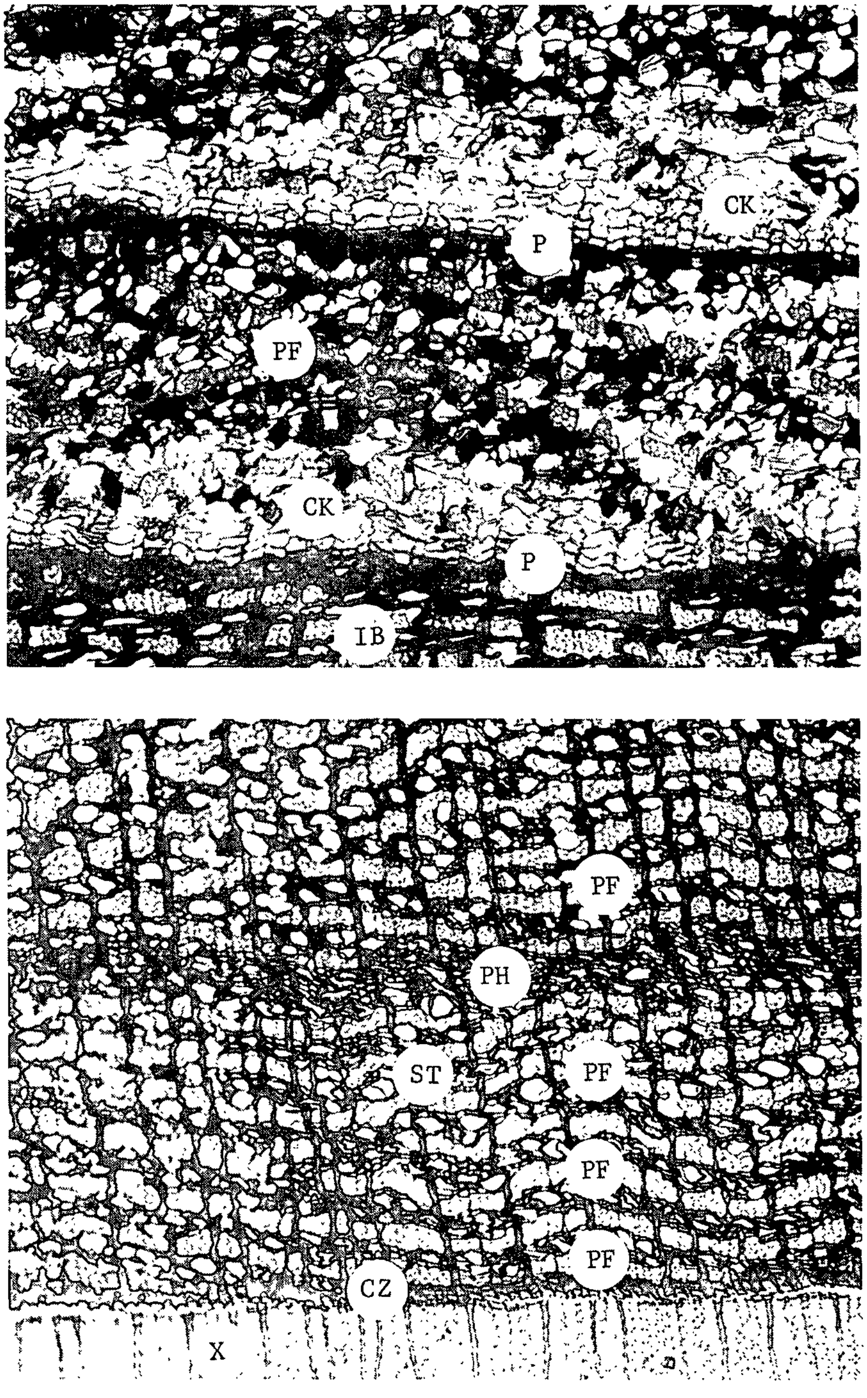

Figure 11. Cross Sections of Black Willow. Photograph on the Bottom Shows the Xylem (X), Cambium Zone (CZ), Tangential Bands of Phloem Fibers (PF), Sieve Tube Elements (ST) and Tangential Bands of Nonfiber Phloem (PH). The Photograph on Top Shows Outer Bark Detail with Two Periderms (P), Inner Bark (IB), Cork Cells (CK) and Phloem Fibers (PF). Magnification — 75X

SPECIFIC GRAVITY OF WOOD AND BARK

Basic to our understanding of bark properties is the knowledge of the specific gravity of both the wood and the bark of various species. This knowledge is useful when considering methods of separating and segregating chip mixtures. Correlations run on wood and bark specific gravity and density at 100% moisture content of the 42 species investigated showed a significant correlation between wood specific gravity and density* and also between bark specific gravity and density. Consequently, it would be possible to predict the flotation characteristics of a species by knowing the bark and wood specific gravity (see section on "Water Flotation Behavior"). Important to the success of a water flotation procedure is a reasonable difference between bark and wood specific gravity of a species and, therefore, between bark and wood density. Information on the specific gravity of a species is also useful when considering mechanical means of segregation and the effect of chipper knives on unbarked logs, hammermilling on chip mixtures, etc., (see section on "Bark Strength, Toughness and Reaction to Hammermilling"). The fuel value of a species is also influenced by the specific gravity of the bark and wood.

Tables IV and V summarize the bark and wood specific gravities of the 42 species investigated. For most species, the hardwood barks were similar or higher in specific gravity than the conifer barks (Engelmann spruce, Virginia pine, eastern cottonwood, yellow poplar and black willow were exceptions). The specific gravity of the hardwood barks investigated showed no consistent relationship to the specific gravity of the wood. For some species, the wood has a higher specific gravity,

*Density, as used in this report, is defined as green weight divided by green volume as contrasted to specific gravity which is dry weight divided by green volume.

for others the bark has the higher specific gravity and there are several species, like sweetgum and yellow-poplar, where the specific gravity of the wood and bark is very similar. The lack of a consistent specific gravity relationship in hardwoods makes the use of a water flotation procedure for mixed hardwood chips virtually impossible except for a few associated species like red alder and northern black cottonwood which have similar densities at the same moisture content.

TABLE IV

SPECIFIC GRAVITY
HARDWOODS

(ovendry weight/green volume)

Species	Wood	Bark		
		Inner	Outer	Total
Quaking aspen	0.38	0.40	0.55	0.50
Eastern cottonwood	0.38	0.29	0.32	0.31
N. black cottonwood	0.31	0.38	0.42	0.40
Black willow	0.36	0.40	0.28	0.34
Sugar maple	0.59	0.69	0.49	0.54
Silver maple	0.42	0.51	0.61	0.57
Red maple	0.51	0.59	0.61	0.60
White birch	0.49	0.57	0.54	0.56
Sycamore	0.45	0.60	--	0.60
Sweetgum	0.44	0.51	0.36	0.42
Yellow-poplar	0.39	0.38	0.42	0.38
Black tupelo	0.52	0.37	0.37	0.40
White ash	0.57	0.51	0.43	0.48
Green ash	0.56	0.49	0.35	0.45
Shagbark hickory	0.65	0.69	0.81	0.72
American beech	0.60	0.67	--	0.67
Red alder	0.37	0.55	0.62	0.58
Post oak	0.64	0.65	0.53	0.56
Pin oak	0.61	0.57	0.74	0.71
Black oak	0.57	0.69	0.68	0.68
Northern white oak	0.64	0.65	0.52	0.58
Southern white oak	0.67	0.70	0.44	0.56
Northern red oak	0.56	0.53	0.71	0.65
Southern red oak	0.60	0.68	0.70	0.70

TABLE V

SPECIFIC GRAVITY
SOFTWOODS

(ovendry weight/green volume)

Species	Wood	Bark		
		Inner	Outer	Total
Loblolly pine	0.45	0.29	0.34	0.33
Slash pine	0.54	0.34	0.36	0.35
Longleaf pine	0.55	0.25	0.48	0.45
Shortleaf pine	0.47	0.26	0.35	0.35
Virginia pine	0.50	0.27	0.56	0.54
Red pine	0.39	0.20	0.29	0.27
Eastern white pine	0.32	0.32	0.53	0.47
Jack pine	0.39	--	0.43	0.41
Lodgepole pine	0.39	0.32	0.45	0.38
Ponderosa pine	0.39	0.34	0.35	0.35
Balsam fir	0.34	0.32	0.46	0.40
Western larch	0.50	0.37	0.33	0.33
White spruce	0.34	--	0.43	0.39
Black spruce	0.40	0.33	0.46	0.42
Engelmann spruce	0.34	0.41	0.52	0.51
Douglas-fir	0.43	0.42	0.40	0.41
Eastern hemlock	0.40	0.40	0.44	0.43
Western hemlock	0.40	0.46	0.45	0.45

A relationship between wood and bark specific gravity has been established for the oaks, however. For trees in the white oak group, which includes northern and southern white oak and post oak, the specific gravity of the wood is higher than that of the bark while for the red oak group (northern and southern red oak, pin oak and black oak) the wood is lower in specific gravity than the bark.

Conifer barks are generally similar to or lower in specific gravity than the associated sapwood (Engelmann spruce and eastern white pine are exceptions). For the southern pines, the wood is higher in specific gravity than the bark and because of the similarity in bark and wood specific gravity of several of the southern pines, it might be possible for a mixture to be segregated through water flotation. It is interesting that lodgepole pine and jack pine are similar morphologically and also have similar wood and bark specific gravities. This is also true of eastern and western hemlock. The importance of the knowledge of the wood and bark specific gravity of a species will be discussed in more detail in the sections dealing with segregation of chip mixtures.

EXTRACTIVES AND FIBROUS YIELDS

EXTRACTIVES

Extractives are often chemical "building blocks" of the tree and occur most abundantly in the bark. Some extractives are responsible for resistance of certain species to biological degradation (4) and are a source of tall oil and turpentine, but they can also result in reduced yield of fibrous material and paper machine "pitch problems." Recent needs to reduce total water use through closed white water systems are expected to accentuate problems in this area. No attempt has been made in this section to go beyond summarizing and discussing the total alcohol-benzene extractives. Such extractives information is expected to provide an appropriate indication regarding possible pitch problems when large amounts of bark are pulped. Further detailed examination of the types of extractives involved is recommended using specific bark sources if preliminary comparisons suggest pitch and yield problems may develop.

According to Binotto and Murphey (5), large differences exist in extractives levels between the inner and outer bark of chestnut oak, with the inner bark containing a higher percentage of extractives. They also found a seasonal variation with much lower percentages of extractives in the summer. These findings would probably also apply to many other species.

There has been no consistent pattern with regard to levels of bark extractives with the exception that the levels in the bark are from about three to eight times higher than in the wood. Browning (6) reported that mineral substances in the bark can be more than ten times higher than in the corresponding wood.

Extractives levels for the wood of all species investigated ranged from 1.0 (red and sugar maple) to 7.4 (eastern white pine). Extractives levels for the bark of all species ranged from 6.0 (red maple and red alder) to 25.4 (eastern hemlock). Most conifer barks have higher levels of extractives than do hardwood barks. Twelve of the 18 conifers investigated had bark extractives levels greater than 10% in contrast to 14 of 24 hardwoods. Red pine and the southern pines (loblolly, slash, shortleaf, longleaf and Virginia pine) were the exceptions with extractives levels from only 5.8 to 8.8%. The three maples investigated (sugar, silver and red maple) were among the lowest in bark extractives levels of the hardwoods, averaging 6.2%. Northern black cottonwood, white birch and black oak are hardwood species with high levels of bark extractives and balsam fir, Engelmann spruce and eastern hemlock are the three conifers with the highest levels of extractives. Even with these latter species, however, pitch problems are not expected to be serious unless, as a result of concentrating large amounts of bark from screening procedures, high levels of bark are pulped. It is also important to remember that seasoning can diminish the content of extractives in bark and our values are based on airdry samples in most cases, rather than fresh samples.*

Although no significant trends could be determined for bark extractives overall, it is interesting to note that lodgepole pine and jack pine, very similar species morphologically, also have similar levels of extractives. Also, bark extractives levels of the red oak group (northern and southern red oak, pin oak and black oak) were much higher than the levels obtained for the white oak group (northern and southern white oak and post oak). Tables VI and VII summarize the alcohol-benzene extractives levels obtained for the wood and bark of all species investigated.

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*Although airdried samples were supplied for analysis, results in Tables VI and VII are expressed on an ovendry basis.

TABLE VI

PERCENT ALCOHOL-BENZENE EXTRACTIVES
HARDWOODS

(airdried samples)

Species	Wood	Bark
Quaking aspen	3.0	15.0
Eastern cottonwood	1.4	7.9
Northern black cottonwood	2.3	20.0
Black willow	2.6	6.9
Sugar maple	1.0	6.0
Silver maple	3.5	6.6
Red maple	1.0	6.0
White birch	4.0	17.0
Sycamore	2.2	8.1
Sweetgum	2.6	10.2
Yellow-poplar	3.9	13.8
Black tupelo	3.0	10.6
White ash	4.0	12.6
Green ash	4.0	12.6
Shagbark hickory	3.2	14.6
American beech	1.5	10.6
Red alder	2.1	6.0
Post oak	4.3	8.2
Pin oak	4.4	14.9
Black oak	5.0	15.4
Northern white oak	2.4	7.2
Southern white oak	4.6	8.6
Northern red oak	4.5	11.0
Southern red oak	4.8	11.6

Although extractives are often thought detrimental to the papermaking process, particularly with the use of whole-tree chips, research and time will undoubtedly eventually prove bark to be a valuable resource. One company in the Pacific Northwest has already turned out several marketable products from Douglas-fir bark, including vegetable wax, plastics extender, cork and a phenol substitute. Environmentally, there is no solid waste residue remaining from the bark they use.

Other sections in this report will speak to the problem of separating and segregating bark and, when that problem is finally solved, perhaps better use can be made of the bark resource.

TABLE VII

PERCENT ALCOHOL-BENZENE EXTRACTIVES
SOFTWOODS

(airdried samples)

Species	Wood	Bark
Loblolly pine	3.0	8.5
Slash pine	3.3	8.4
Longleaf pine	4.3	8.8
Shortleaf pine	4.1	7.7
Virginia pine	4.1	8.2
Red pine	3.5	5.8
Eastern white pine	7.4	15.5
Jack pine	3.9	15.3
Lodgepole pine	3.5	15.7
Ponderosa pine	5.3	15.7
Balsam fir	2.0	19.5
Western larch	1.4	14.4
White spruce	2.2	16.0
Black spruce	1.5	14.7
Engelmann spruce	2.8	24.4
Douglas-fir	4.0	16.4
Eastern hemlock	3.7	25.4
Western hemlock	1.6	11.7

FIBROUS YIELD

Auchter and Horn (7) published an interesting paper on the economics of kraft pulping of unbarked wood in which they estimated a savings of approximately 3 million dollars in capital cost for a kraft pulp mill if chips were pulped with bark included. A savings of $1,000,000 alone could result from the elimination of debarking equipment. However, Keays and Hatton (8) indicated there would be major monetary losses if daily production was reduced by 10% because the mill was "digester-limited" and pulp production was decreased as a result of pulping wood/bark mixtures.

Because of the projected wood shortages and the push for greater utilization of the forest resource, increasing emphasis is being placed on pulping bark rather than debarking bolts or segregating wood/bark chip mixtures. Important to determining the usefulness of this approach with a particular species is determining the proportion of lignified cells that exist in the bark and that will survive normal cooking procedures. Also, it is important to determine what percentage of these cells will contribute in a favorable way to the resulting paper product.

Marton, et al. (9), working with red pine and sugar maple, reported that 30-35% more pulp can be obtained from the whole tree than from its merchantable part alone. However, the most difficult problem was created by branches up to one inch in diameter, as they contained up to 39% bark. This bark contained 10-20 times more ash than did the wood and 3-5 times more extractives. Horn and Auchter (10) estimated the net gain in yield of acceptable pulp per rough cord would be at least 4% higher for unbarked chips when pulping a number of western species. Another 5-10% gain in yield could be realized because of little or no white wood loss incurred during debarking.

The increased interest in the use of whole-tree chips prompted the adding of bark fibrous yield to the characterization of important pulpwood species. The elements found in pulped bark that are of importance to the pulp and paper industry are phloem fibers, sclereids or phellem cells and sieve cells or sieve tube elements. These elements are discussed in the section on "Wood and Bark Morphology." Phloem fibers are a positive influence, adding to the total yield of fibrous material.

Sclereids and phellem cells, if not fully cooked, could remain in clumps and cause so-called "fisheyes" in certain grades (calendered) of paper. Thin-walled sieve cells or sieve tube elements are also often present in considerable numbers in bark pulps and could be used as filler material in paper. However, it is questionable, other than an increase in pulp yield, whether they would contribute in any useful way to paper properties. When subjected to beating, they probably would not fibrillate to any appreciable extent. Sieve cells and sieve tube elements could also conceivably contribute to felt plugging and drainage problems if built up in sufficient quantities through the use of a closed system. Figures 12 and 13 illustrate the elements found in pulped hardwood and softwood bark.

Hardwoods

Table VIII summarizes bark pulping results for the hardwoods investigated. Most hardwood barks contain fiber. The only exceptions found in this study were white birch, sycamore and red alder. In addition, the hardwoods generally had fairly low numbers of sclereids retained in the usable part of the pulp, despite much higher levels in the total bark. Several of the hardwoods gave surprisingly high solids yields (46.2% for post oak and 40.0% for black willow)*. The average bark solids yield for all the hardwoods investigated was 33.4%. Black willow, white ash and shagbark hickory were the species with the greatest amount of usable fiber (15-21%) and all three species also had either no sclereids in the bark or the amounts were very low. In addition, black willow is low in alcohol-benzene extractives, making it one of the most attractive species for whole-tree pulping. Eastern cottonwood and yellow-poplar are additional species with some fiber in the bark but no sclereids.

*See "Experimental Procedures" for a description of the cooking conditions.

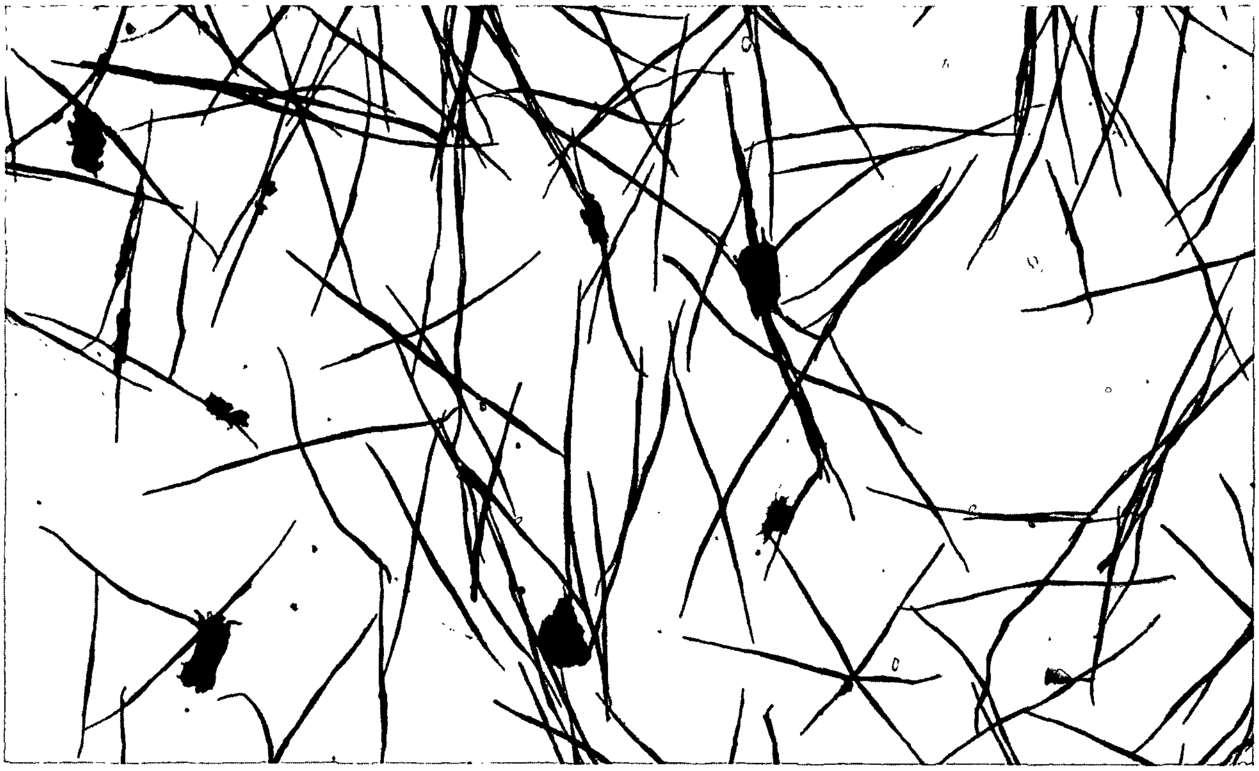

Figure 12. Illustrated are the Elements Found in Pulped Quaking Aspen Bark and Retained on a 60-mesh Screen. Retained were Mostly Phloem Fibers Along with Very Small Amounts of Sclereids. Magnification — 35X

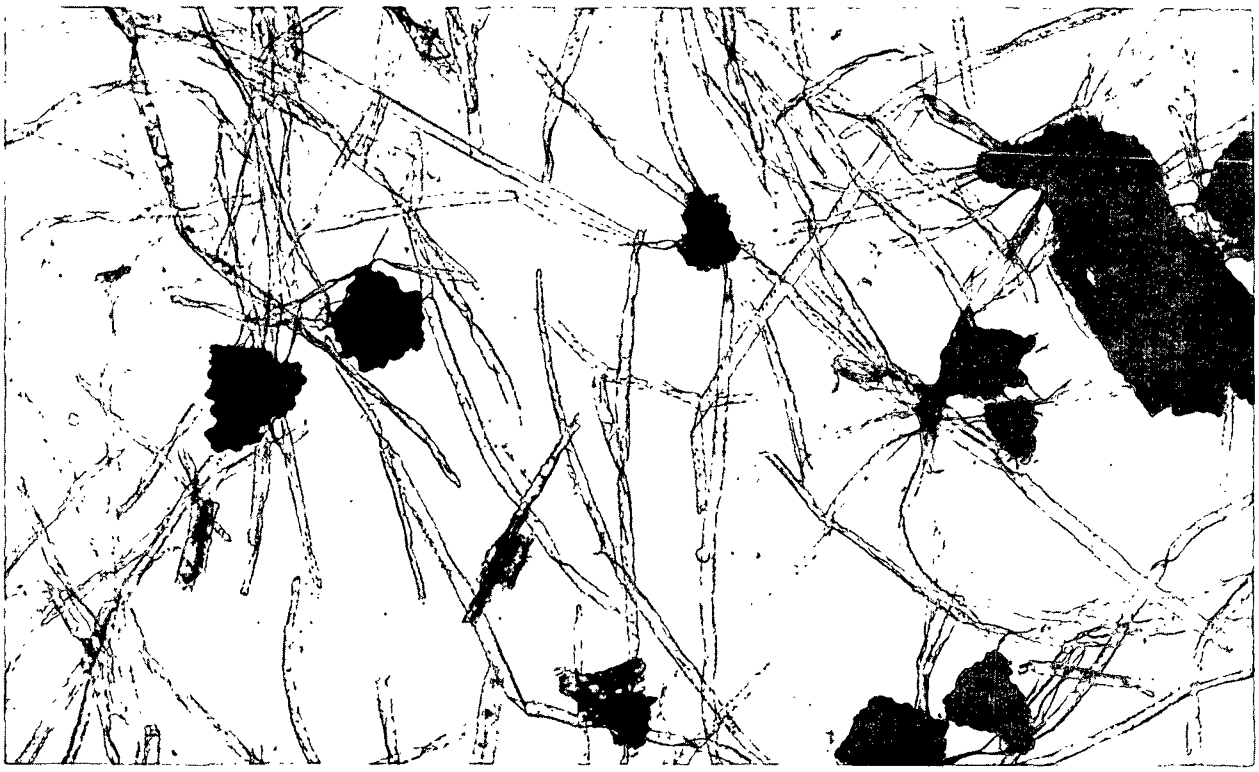

Figure 13. Illustrated are the Elements Found in Pulped Loblolly Pine Bark and Retained on a 60-mesh Screen. Retained were Mostly Sieve Cells Along with Some Clumps of Phellem Cells. Magnification — 35X

TABLE VIII

BARK PULPING RESULTS[a]
HARDWOODS

Species	Pulp Yield, %	Usable Bark Fiber, %	Sclereids or Phellem Cells Remaining
Quaking aspen	33.8	10	1
Eastern cottonwood	35.4	9	<0.1
Northern black cottonwood	26.0	12	0
Black willow	40.0	21	0.3
Sugar maple	33.9	3	0.2
Silver maple	32.0	6	2.5
Red maple	32.0	12	0.9
White birch	36.3	0	0.7
Sycamore	31.4	0	0
Sweetgum	34.9	5	0
Yellow-poplar	32.3	13	0
Black tupelo	31.4	1-10	0
White ash	35.7	16	0
Green ash	38.0	13	0.8
Shagbark hickory	28.3	15	0
American beech	37.0	0.25	0
Red alder	27.0	0	0
Post oak	46.2	4	0
Pin oak	26.5	2	0
Black oak	31.4	5	0
Northern white oak	35.4	3	0
Southern white oak	36.6	3	0
Northern red oak	28.4	5	0.2
Southern red oak	30.7	4	0

[a]Usable bark fiber and sclereids remaining are the fibers and sclereids retained on 60- and 100-mesh screens.

Sycamore, American beech and red alder are examples of species where the inclusion of bark would have little effect on the pulp of whole-tree chips. All three species contain little or no fiber in the bark and most of the pulped bark is lost in washing and screening operations. Sycamore and red alder are also low in alcohol-benzene extractives while American beech is intermediate.

Table IX gives a comparison of the average arithmetic fiber length for both the wood and bark of several species. It is interesting that bark fiber lengths compare favorably with wood fiber lengths and gives further impetus to the option of pulping the bark when it is contained in chip mixtures for a number of hardwoods. It is important to remember, however, that clusters of phloem fibers could also present a problem if not dispersed.

TABLE IX

COMPARISON OF WOOD AND BARK FIBER LENGTHS
FOR SEVERAL SPECIES

Species	Average Arithmetic Length, mm	
	Wood	Bark[a]
Quaking aspen	1.04	1.19
Black willow	1.10	1.20
Sugar maple	0.80	0.99
Red maple	0.70	1.10
Sweetgum	1.70	0.95
Yellow-poplar	1.90	1.20
Black tupelo	1.80	1.25
Northern white oak	1.40	1.09
Northern red oak	1.40	1.04

[a]Based on fibers retained on a 60-mesh screen.

Softwoods

Table X summarizes bark pulping results for the softwoods investigated. Softwoods are not nearly as attractive a possibility for pulping as are hardwoods. Most of the species investigated contained little or no fiber. The only exceptions were Douglas-fir and western larch. There is also evidence in the literature (11, 12) that western red cedar, along with several other species in the Cupressaceae family, also have fiberlike elements in the bark. In addition, softwoods tend to be higher than hardwoods in alcohol-benzene extractives and also contain, proportionally, greater numbers of sclereids or phellem cells. (Hemlock, fir and spruce contain sclereids while phellem cells are found in the pines.)

TABLE X

BARK PULPING RESULTS[a]
SOFTWOODS

Species	Pulp Yield, %	Usable Bark Fiber, %	Sclereids or Phellem Cells Remaining
Loblolly pine	23.6	0	1
Slash pine	23.6	0	2
Longleaf pine	26.4	0	<1
Shortleaf pine	20.1	0	<1
Virginia pine	23.2	0	<1
Red pine	33.0	0	<1
Eastern white pine	30.5	0	<1
Jack pine	18.6	0	<1
Lodgepole pine	27.4	0	<1
Ponderosa pine	29.1	0	<1
Balsam fir	26.0	0	12
Western larch	27.8	1	0
White spruce	20.6	0	2
Black spruce	26.0	0	3
Engelmann spruce	24.4	0	3
Douglas-fir	17.6	5	2
Eastern hemlock	35.0	0	4
Western hemlock	35.8	0	11

[a]Usable bark fiber and sclereids remaining are the fibers and sclereids retained on 60- and 100-mesh screens.

Western larch is probably the best candidate for whole-tree pulping of the species investigated as it contains a small amount of fiber in the bark but is lacking in sclereids. However, even in this species, the fibers are of questionable value since they are extremely stiff, would not fibrillate and would have low bonding strength. Average solids yield for the softwoods investigated was 26.0%, compared to 33.4% for the hardwoods.

It appears that removal of at least part of the bark would be desirable in most cases for softwood chip mixtures. This approach is covered more fully in the sections on "Wood/Bark Adhesion," "Bark Strength, Toughness and Reaction to Hammermilling," and "Water Flotation Behavior." Factors to be considered when deciding whether to try pulping whole-tree chips without removal of the bark are problems with lower pulp yields, brightness, higher permanganate number, and greater chemical consumption. The amount of bark tolerated in the pulp furnish and the efforts expended to separate and segregate bark will be determined in part by its value for fuel or its use for chemicals and board (13). Individual reports should be consulted for a more comprehensive summary of the bark pulping results for species of interest.

WOOD/BARK ADHESION

Wood/bark adhesion differences are believed to be one of the reasons for the variation encountered in the ease of debarking pulpwood species. Bark thickness and bark toughness are additional factors influencing drum debarking (14, 15). The same factors that influence debarking of pulpwood species are expected to influence the debarking of wood chips. The approach taken in this study has been to obtain growing season and dormant season information on: (1) magnitude of wood/bark adhesion, (2) morphological structures associated with wood/bark adhesion, and (3) reasons for differences between species in adhesion.

Using a sampling and testing procedure described in the "Experimental Procedures Section," shear parallel to the grain was measured on appropriately collected samples. Upon completion of the adhesion tests, failure zones were examined to determine the failure zone location and the associated bark morphology. Preliminary wood/bark adhesion measurements conducted throughout the year for several tree species made it possible to limit subsequent measurements to twice during the year. This resulted in the establishment of a procedure involving collections from two or three trees during the dormant season and a similar two or three-tree collection during the growing season. Growing season sampling was discontinued after measurements were completed on 22 species, including both conifers and hardwoods, when little variation was encountered in adhesion values (3-6 kg/cm^2). Growing season failure zones quite consistently were located in the cambium zone or in the newly-formed and only partially lignified xylem elements just inside the cambium zone.

Dormant season wood/bark adhesion is the important parameter associated with debarking problems and dormant season values were measured for 42 pulpwood species. As a result of the measurement data taken (Tables XI and XII) and based

TABLE XI

BETWEEN-SPECIES COMPARISONS OF WOOD/BARK ADHESION
HARDWOODS

Species	Wood/Bark Adhesion, kg/cm² Peeling Season[a]	Dormant Season
Quaking aspen	6.4	11.4
Eastern cottonwood	4.4	13.5
Northern black cottonwood	--	18.7
Black willow	--	17.6
Sugar maple	5.8	10.1
Silver maple	6.1	14.1
Red maple	--	12.4
White birch	5.1	12.0
Sycamore	--	14.8[b]
Sweetgum	10.2	15.3
Yellow-poplar	--	16.6
Black tupelo	--	13.5
White ash	--	23.8
Green ash	--	17.4
Shagbark hickory	3.8	30.6
American beech	--	9.3
Red alder	--	13.0
Post oak	--	12.2
Pin oak	--	12.9
Black oak	--	21.5
Northern white oak	4.8	7.8
Southern white oak	--	7.2
Northern red oak	2.5	8.4
Southern red oak	5.4	8.2

[a]Dashes mean that adhesion was not measured for those species during the growing season.
[b]Samples failed in tensile.

upon observations made on the failure zone, it became clear that for hardwoods, dormant season wood/bark adhesion was related to inner bark strength and inner bark morphology. Dormant season wood/bark adhesion for conifers appeared to be less closely related to bark strength and bark morphology. These relationships are discussed further in the sections that follow.

TABLE XII

BETWEEN-SPECIES COMPARISONS OF WOOD/BARK ADHESION
SOFTWOODS

Species	Wood/Bark Adhesion, kg/cm^2 Peeling Season[a]	Wood/Bark Adhesion, kg/cm^2 Dormant Season
Loblolly pine	5.8	5.5
Slash pine	3.5	9.1
Longleaf pine	--	22.0
Shortleaf pine	--	8.6
Virginia pine	--	7.2
Red pine	--	9.6
Eastern white pine	--	7.3
Jack pine	4.0	10.7
Lodgepole pine	2.2	5.6
Ponderosa pine	5.0	9.6
Balsam fir	2.4	9.0
Western larch	1.2	4.4
White spruce	4.4	10.3
Black spruce	--	18.1
Engelmann spruce	3.4	12.5
Douglas-fir	3.4	8.0
Eastern hemlock	--	14.3
Western hemlock	3.6	8.2

[a]Dashes mean that adhesion was not measured for those species during the growing season.

HARDWOODS

Hardwood dormant season wood/bark adhesion varied from 30.6 kg/cm^2 for shagbark hickory to 7.2-7.8 kg/cm^2 for white oak. The relationships that exist between hardwood dormant season wood/bark adhesion and bark strength and morphology were examined by running a series of simple and multiple correlations between wood/bark adhesion and wood specific gravity, bark specific gravity, percent bark fiber, percent sclereids, wood toughness, bark toughness, total bark strength and inner bark strength. Table XIII summarizes the simple correlation matrix involved. Hardwood wood/bark adhesion was found to be positively correlated with percent bark fibers, wood toughness, bark toughness, inner bark strength and inner + outer bark strength. Wood/bark adhesion was negatively correlated with the percent sclereids in the bark. A number of multiple regressions were run in an effort to determine those variables that would be most useful in estimating wood/bark adhesion. The percent bark fiber, wood toughness and inner bark strength proved to be the most useful of the variables investigated. Bark toughness was also highly correlated with wood/bark adhesion but was not used in the final multiple regressions because it was correlated with several of the other parameters.

Table XIV summarizes the data for the three most promising prediction equations. Based upon F-tests and R^2 values, Equation III using wood toughness and inner bark strength turned out to be the most useful equation. This equation reads:

$$\hat{Y} = 0.59 + 3.31\, X_1 + 0.71\, X_2$$

where $\hat{Y}$ = hardwood dormant season wood/bark adhesion
X_1 = wood toughness
X_2 = inner bark strength.

TABLE XIII

SIMPLE CORRELATIONS BETWEEN HARDWOOD
WOOD AND BARK CHARACTERISTICS[a]

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wood/bark adhesion (1)	1.0	-0.09	-0.05	0.59**	-0.56**	0.40	0.72**	0.78**	0.83**
Wood specific gravity (2)		1.0	0.64	-0.29	0.36	0.73**	0.32	0.16	-0.11
Bark specific gravity (3)			1.0	-0.48*	0.50	0.62**	0.26	0.20	-0.22
% Bark fibers (4)				1.0	-0.60**	-0.03	0.51*	0.45*	0.68**
% Sclereids (5)					1.0	0.20	-0.38	-0.41*	-0.68**
Wood toughness (6)						1.0	0.65**	0.63**	0.29
Bark toughness (7)							1.0	0.92**	0.68**
Bark strength[b] (8)								1.0	0.76**
Inner bark strength (9)									1.0

[a]Values from 0.404 to 0.515 significant at 0.95 level of probability (*). Values greater than 0.515 significant at 0.99 level of probability (**).
[b]Average of inner and outer bark values.

TABLE XIV

MULTIPLE REGRESSION PREDICTIONS OF HARDWOOD WOOD/BARK ADHESION

Independent Variables	Partial Regression Coefficients	T-test[a]
I. % Fiber	0.12	0.8
Wood toughness	3.91	1.6
Inner bark strength	0.62	3.9
Regr. constant = 0.55, $F_{3,20}$[b] = 17.48**, R^2 = 0.72		
II. % Fiber	0.55	3.9
Wood toughness	7.90	2.7
Regr. constant = 0.55, $F_{2,21}$[b] = 11.16**, R^2 = 0.52		
III. Wood toughness	3.31	1.4
Inner bark strength	0.71	6.4
Regr. constant = 0.59, $F_{2,21}$[b] = 26.39**, R^2 = 0.72		

[a]Test for significance of regression coefficients, values >1.9 considered significant at 0.95 probability level.
[b]Test for significance of regression, * indicates significance at 0.95 level and ** indicates significance at 0.99 probability level.

Morphologically, the presence of fibers increases inner bark strength and, when sclereids are present, bark strength is decreased. Inner bark strength, in turn, has a major influence on hardwood wood/bark adhesion. The multiple regression equation employing wood toughness and inner bark strength accounts for 72% of the wood/bark adhesion variation encountered.

CONIFERS

Conifer dormant season wood/bark adhesion varied from 18.1 kg/cm^2 for black spruce to 4.4 kg/cm^2 for western larch, with the majority of the conifer species tested having lower dormant season values (5.0-10.0 kg/cm^2) than the hardwoods (8.0-24.0 kg/cm^2). The relationship that exists between wood/bark adhesion and bark strength and morphology was examined by running, as for the hardwoods, a series of simple and multiple correlations using wood specific gravity, bark specific gravity, percent bark fiber, percent sclereids, wood toughness, bark toughness and bark strength. Table XV summarizes the simple correlation matrix generated. Conifer wood/bark adhesion was not correlated with specific gravity or the morphological parameters examined but was positively correlated with total bark strength and inner bark strength.

A number of multiple regressions (Table XVI) were run in an effort to determine those independent variables that could be used to predict conifer dormant season wood/bark adhesion. The lack of bark fibers in most species of conifers and the apparent minor influence of sclereidlike structures on bark strength reduced the usefulness of these two parameters in predicting wood/bark adhesion. Wood specific gravity and inner bark strength, as in the hardwoods, did prove to be useful independent variables that could be used to predict wood/bark adhesion for softwood species. The most useful prediction equation obtained was:

$$\hat{Y} = 0.14 - 23.85\ X_1 + 0.93\ X_2$$

where $\hat{Y}$ = conifer dormant season wood/bark adhesion
X_1 = wood specific gravity
X_2 = inner bark strength.

Although the tests for significance of the above regression is highly significant, the regression equation accounts for only 49% of the variation encountered. Of particular interest is the fact that in the case of both the hardwoods and the conifers, inner bark strength was an important determining factor in dormant season wood/bark adhesion.

TABLE XV

SIMPLE CORRELATIONS BETWEEN SOFTWOOD
WOOD AND BARK CHARACTERISTICS

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wood/bark adhesion (1)	1.0	-0.40	0.17	-0.15	-0.16	-0.10	0.23	0.48*	0.50*
Wood specific gravity (2)		1.0	0.12	0.10	0.19	0.58*	-0.11	0.01	0.15
Bark specific gravity (3)			1.0	-0.02	0.10	-0.09	0.51*	0.08	0.00
% Bark fibers (4)				1.0	-0.30	0.07	0.49*	-0.01	0.05
% Sclereids (5)					1.0	0.39	-0.20	-0.10	-0.13
Wood toughness (6)						1.0	0.09	0.02	0.32
Bark toughness (7)							1.0	0.46	0.44
Bark strength[b] (8)								1.0	0.86**
Inner bark strength (9)									1.0

[a]Values from 0.468 to 0.590 significant at 0.95 level of probability (*). Values greater than 0.590 significant at 0.99 level of probability (**).
[b]Average of inner and outer bark values.

TABLE XVI

MULTIPLE REGRESSION PREDICTIONS OF
SOFTWOOD WOOD/BARK ADHESION

Independent Variables	Partial Regression Coefficients	T-test[a]
I. Wood specific gravity	-24.82	2.6
Bark toughness	-8.24	0.5
Inner bark strength	1.01	2.9
Regr. constant = 0.15, $F_{3,14}$[b] = 4.57*, R^2 = 0.49		
II. Wood specific gravity	-23.85	2.6
Inner bark strength	0.93	3.1
Regr. constant = 0.14, $F_{2,15}$[b] = 7.08**, R^2 = 0.49		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

BARK STRENGTH, TOUGHNESS AND REACTION TO HAMMERMILLING

Bark strength and toughness measurements have been included as part of the bark characterization research because it was felt that these measurements, when compared with the data on wood/bark adhesion, hammermilling, bark morphology, and with differences encountered in conventional debarking, would shed light on how best to separate and segregate bark from wood. It was also felt that by making comparisons over a broad range of species, our understanding of the critical factors involved would increase to the point that some extrapolation of results to species that have not been completely evaluated would be possible.

Hammermilling has been widely used in bark utilization to prepare fractions for use as horticultural mulch, soil conditioners, and as additives to a number of types of products. Hammermilling, or some mechanical treatment similar to hammermilling, is being suggested as one step in a screening procedure that would be appropriate for use on wood/bark mixtures high in amounts of bark. A simulated hammermilling procedure was developed in an effort to relate hammermilling of bark (and wood) to bark strength, toughness and morphology. A Micro Pulverizer was modified so that the action of this device simulated the action of conventional hammermilling and, at the same time, was a procedure that could be run on small samples of bark and wood. Pure fractions of either wood or bark were fed into the hammermilling apparatus, caught in a cloth bag and screened. The results indicate hammermilling, followed by screening, can be expected to result in a moderate reduction in levels of bark for a number of pulpwood species. No attempt has been made to optimize the action of this simulated hammermilling procedure and there is reason to believe that, by modifying the mechanical action employed and using improved screening procedures, the effectiveness of this approach could be greatly improved.

Tables XVII and XVIII summarize the toughness, bark strength and hammermilling results for the hardwood and conifer species investigated. The bark toughness measurements were made upon small tabs of carefully prepared wood, inner bark and outer bark samples. The tests were run on the Instron tester and the values given in the table represent average values for two or three trees*. The toughness values represent the energy required to rupture a thin specimen by a bending force perpendicular to the grain (parallel to tree diameter). The original measurements were made and given in the species reports, with outer and inner bark recorded separately. Quite consistently, inner bark toughness was greater than that of the outer bark for both the hardwoods and conifers. However, to facilitate between-species comparisons, the weighted average values are given in Tables XVII and XVIII. There turned out to be no major overall differences in the toughness of hardwood and softwood barks. The several exceptions are those species that have large amounts of fiber or fiberlike elements in the bark (ash, hickory, Douglas-fir). Wood toughness also appears to be correlated to a certain degree with wood specific gravity and this correlation, along with a number of others, will be considered in the sections that follow. Because of major differences between hardwoods and conifers in bark morphology and bark strength characteristics, the data on reaction to hammermilling was handled separately for the two groups of species.

HARDWOODS

Bark Strength

Weighted average bark strength** values for hardwoods included a high value of 52.2 kg/cm^2 for shagbark hickory and varied from 3.0 kg/cm^2 for sugar

*Additional details on the testing procedures used are given in the section on "Experimental Procedures."

**Weighted on the basis of percent inner and outer bark in the tree samples.

maple to 11.6 kg/cm^2 for yellow-poplar. Simple correlations run between bark strength and the variables given in Table XIII revealed that weighted average bark strength was positively correlated with percent bark fibers and negatively correlated with percent sclereids in the bark. In addition, bark strength was positively correlated with wood toughness, bark toughness and wood/bark adhesion.

TABLE XVII

SUMMARY OF BARK STRENGTH, TOUGHNESS
AND HAMMERMILLING RESULTS
HARDWOODS

Species	Weighted Bark Strength, kg/cm^2	Weighted Bark Toughness	Wood Toughness	Hammermilling: Bark Removed, %	Hammermilling: Wood Loss, %
Quaking aspen	8.2	0.20	0.30	34	5
Eastern cottonwood	7.8	0.12	0.27	18	5
N. black cottonwood	11.1	0.09	0.30	26	5
Black willow	9.3	0.19	0.44	13	4
Sugar maple	3.0	0.17	0.62	29	5
Silver maple	3.4	0.16	0.50	14	4
Red maple	11.3	0.32	0.63	18	4
White birch	3.6	0.10	0.44	38	6
Sycamore	6.1	0.15	0.50	45	7
Sweetgum	6.0	0.14	0.28	32	7
Yellow-poplar	11.6	0.19	0.23	23	7
Black tupelo	10.1	0.20	0.56	39	5
White ash	11.3	0.31	0.68	24	6
Green ash	9.4	0.28	0.64	32	5
Shagbark hickory	52.2	0.79	1.48	11	4
American beech	7.4	0.12	1.02	43	6
Red alder	8.0	0.09	0.50	48	8
Post oak	5.0	0.19	0.66	47	6
Pin oak	10.2	0.19	0.64	33	6
Black oak	10.8	0.20	0.86	37	7
Northern white oak	3.9	0.13	0.62	37	5
Southern white oak	4.7	0.11	0.98	38	5
Northern red oak	3.6	0.16	0.42	34	10
Southern red oak	3.5	0.13	0.55	46	6

TABLE XVIII

SUMMARY OF BARK STRENGTH, TOUGHNESS
AND HAMMERMILLING RESULTS
SOFTWOODS

Species	Weighted Bark Strength, kg/cm^2	Weighted Bark Toughness	Wood Toughness	Hammermilling Bark Removed, %	Hammermilling Wood Loss, %
Loblolly pine	3.2	0.06	0.54	34	6
Slash pine	5.3	0.09	0.54	36	5
Longleaf pine	5.8	0.11	0.89	35	6
Shortleaf pine	3.2	0.11	0.94	29	4
Virginia pine	4.1	0.18	0.61	31	4
Red pine	5.6	0.13	0.64	26	5
Eastern white pine	5.4	0.15	0.36	29	4
Jack pine	2.3	0.07	0.34	26	5
Lodgepole pine	2.4	0.08	0.28	31	4
Ponderosa pine	4.9	0.08	0.26	26	4
Balsam fir	1.6	0.06	0.42	44	6
Western larch	4.5	0.10	0.28	26	6
White spruce	7.4	0.16	0.34	23	4
Black spruce	8.6	0.14	0.45	26	6
Engelmann spruce	4.2	0.18	0.26	25	4
Douglas-fir	4.7	0.21	0.58	28	8
Eastern hemlock	5.8	0.12	0.60	25	5
Western hemlock	6.0	0.11	0.28	24	3

Using the simple correlation information as a guide, multiple regressions were run in an effort to examine the possibility of predicting bark strength from either morphological information or some other measured parameter such as bark toughness. Table XIX summarizes the results of three of the multiple regression equations that resulted. The results of these calculations and several other computer runs, not given in Table XIX, lead to the conclusion that bark strength could be best predicted from bark toughness. Although bark strength was related to the percent bark fibers and the sclereid level, multiple regressions employing these two variables failed to provide a satisfactory prediction equation. Equation I (Table XIX) indicates wood toughness and wood/bark adhesion could be used to predict bark strength but this is not a very practical approach. Use of bark toughness with the percent bark fibers (Equation II) and bark toughness in combination with sclereid levels give satisfactory prediction equations but neither morphological characteristic improved significantly the prediction equations over the use of bark toughness alone. Bark toughness alone accounted for about 85% of the variation encountered and the addition of the percent sclereids to the prediction equation only increases this figure to 86% (Equation III).

TABLE XIX

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION FOR HARDWOOD BARK STRENGTH

Independent Variables		Partial Regression Coefficients	T-test[a]
I.	Wood toughness	12.89	3.0
	Wood/bark adhesion	1.13	5.0
	Regr. constant = -0.147, $F_{2,21}$[b] = 27.73**, R^2 = 0.73		
II.	Percent fibers	-0.03	0.2
	Bark toughness	63.73	9.6
	Regr. constant = -0.311, $F_{2,21}$[b] = 60.26**, R^2 = 0.85		
III.	Percent sclereids	-0.09	0.8
	Bark toughness	61.26	10.0
	Regr. constant = -0.210, $F_{2,21}$[b] = 62.23**, R^2 = 0.86		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

Bark Toughness

Weighted average bark toughness values for hardwoods included a high value of 0.79 for shagbark hickory and varied from 0.32 for red maple to 0.09 for northern black cottonwood and red alder. Simple correlations run and reported in the Wood/Bark Adhesion Section (Table XIII) revealed that bark toughness was positively correlated with wood/bark adhesion, percent bark fibers, wood toughness and bark strength (both inner and weighted average). The presence of sclereids apparently decreased bark toughness but the correlation coefficient (-0.38) was not quite significant at the 95% probability level.

Multiple regressions were run using a number of independent variables in an attempt to determine those variables that are related to bark toughness and that could be used in predicting bark toughness. Table XX summarizes three of the most promising equations. Equation I ($\hat{Y} = -0.33 + 0.89 X_1 + 0.02 X_2 + -0.01 X_3$) demonstrated that bark specific gravity (X_1), percent fibers (X_2) and the percent sclereids (X_3) could be employed to predict bark toughness, the equation accounting for 66% of the variation encountered. Equations II and III, which include bark strength as an independent variable, do a better job of predicting bark toughness than Equation I, but are essentially no better than using bark strength alone. Of primary interest is that bark toughness is related to, and can be predicted from, three relatively easily measured bark properties (specific gravity, percent fibers and percent sclereids).

TABLE XX

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION FOR HARDWOOD BARK TOUGHNESS

Independent Variables		Partial Regression Coefficients	T-test[a]
I.	Bark specific gravity	0.89	4.9
	Percent fibers	0.02	3.9
	Percent sclereids	-0.01	2.2
	Regr. constant = -0.33, $F_{3,20}{}^{b}$ = 13.14**, R^2 = 0.66		
II.	Bark specific gravity	0.29	2.5
	Percent fibers	0.007	2.7
	Bark strength	0.01	7.7
	Regr. constant = -0.11, $F_{3,20}{}^{b}$ = 56.79**, R^2 = 0.89		
III.	Bark specific gravity	0.09	0.9
	Bark strength	0.01	10.8
	Regr. constant = 0.27, $F_{2,21}{}^{b}$ = 62.83**, R^2 = 0.86		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

Reaction to Hammermilling

Bark removal by a hammermilling-screening procedure and wood losses using a similar procedure are of particular interest because of the possibility of using such a technique to reduce bark levels in chip fractions high in bark. The basic premise is that bark is weaker than wood and appropriate mechanical action will result in the reduction of the size of the bark particles and allow removal by screening. Use of such a procedure has the advantage that, if the material is handled dry, those fine-sized fractions that are separated out by screening would have appreciable value as fuel. Consistently, wood toughness was higher than bark toughness and any mechanical action that could capitalize on the toughness differences between wood and bark could be used to upgrade chip quality. No attempt was made in this study to optimize the hammermilling procedure or the screening technique used in removing the modified bark particles. The fairly major difference in morphology of the hammermilled wood versus the hammermilled bark suggests improved screening procedures (different types of holes and screen movement) would increase bark removal and reduce wood loss.

Bark removal for the hardwoods varied from only 11% for shagbark hickory to 46% for southern red oak, 47% for post oak and 48% for red alder. Wood losses due to hammermilling varied very little from species to species with nearly all species measured having between 4 and 8% wood loss. The exceptions were northern red oak which had a 10% wood loss and western hemlock in which the wood loss was only 3%. To examine the relationship between wood and bark properties and the effectiveness of hammermilling, simple and multiple correlations were run using the variables given in Appendix Table XXXIV. This same table provides the simple correlation matrix that was developed for the hardwoods investigated.

Bark removal was positively correlated with percent sclereids and wood loss and was negatively correlated with percent bark fibers, bark toughness, and both weighted average bark strength and inner bark strength. Multiple regressions were run using the most promising independent variables as determined by the simple correlation matrix. Table XXI gives the most promising resulting prediction equations. Hardwood bark removal by hammermilling was predicted with only a moderate degree of success. Equation I, which uses bark specific gravity and percent bark fibers as independent variables, accounted for 58% of the encountered variation. This equation, however, was no more useful than using percent bark fibers alone. Bark toughness and inner bark strength were each negatively correlated with bark removal by hammermilling but, because they were correlated with each other (not independent) they normally should not be used in the same regression equation (Equation II). When bark toughness is combined with bark specific gravity (Equation III), the resulting equation accounts for approximately 49% of the encountered natural variation, less than that accounted for the percent bark fibers alone (58%). The extremely interesting and useful relationship that is evident from these comparisons is that barks having high levels of fibers have reduced levels of bark removal. The fibrous bark not removed has the advantage that it adds useful fibers to the resulting pulp.

TABLE XXI

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION
FOR HARDWOOD BARK REMOVAL BY HAMMERMILLING

	Independent Variables	Partial Regression Coefficients	T-test[a]
I.	Bark specific gravity	-3.28	0.2
	Percent fibers	-1.50	4.9
	Regr. constant = 0.44, $F_{2,21}$[b] = 14.72**, R^2 = 0.58		
II.	Bark specific gravity	46.88	2.5
	Bark toughness	-50.45	2.4
	Inner bark strength	0.01	0.03
	Regr. constant = 0.16, $F_{3,20}$[b] = 6.37**, R^2 = 0.49		
III.	Bark specific gravity	46.60	3.12
	Bark toughness	-50.00	3.91
	Regr. constant = 0.16, $F_{2,21}$[b] = 10.0**, R^2 = 0.49		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

Effectiveness of Hammermilling

The effectiveness of hammermilling, which is defined as the percent bark removed minus the wood loss, was also investigated using simple and multiple correlation procedures. The results of this series of calculations turned out to be very similar to those cited in the previous section for bark removal by hammermilling. Effectiveness of hammermilling was found to be positively correlated with percent sclereids, and the percent bark removed and negatively correlated with the percent fibers, bark toughness, wood/bark adhesion and both inner and weighted average bark strength.

Multiple regressions were run in which wood specific gravity, bark specific gravity, percent fibers, percent sclereids, bark toughness and inner bark strength were considered and used in various combinations to predict the "effectiveness of hammermilling." Table XXII illustrates two of the most promising equations developed. Neither Equations I or II provide any better estimate of the effectiveness of hammermilling than would be obtained by using the percent bark fibers alone. This single independent variable accounts for about 57% of the variation encountered. The bottom line for "effectiveness of hammermilling" is that the presence of bark fibers reduces the usefulness of this procedure; however, the type of bark that remains after screening is for many species high in fiber and can be expected to contribute in a positive way to pulp yield.

CONIFERS

Bark Strength

Weighted average bark strength for the conifer species investigated tended to vary less (range 1.6-8.6 kg/cm^2) and average less than for the hardwoods studied. Tables XVII and XVIII summarize the values for hardwoods and conifers. Balsam fir had the lowest bark strength and black spruce the highest. Simple correlations run between bark strength and the other previously described variables (see Appendix Table XXXV) revealed that conifer bark strength was positively correlated with wood/bark adhesion and inner bark strength and negatively correlated with bark removal.

TABLE XXII

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION
FOR HARDWOOD EFFECTIVENESS OF HAMMERMILLING

Independent Variables	Partial Regression Coefficients	T-test[a]
I. Wood specific gravity	10.27	0.7
Percent fibers	-1.38	4.2
Percent sclereids	-0.10	0.4
Regr. constant = 0.31, $F_{3,20}{}^{b}$ = 9.26**, R^2 = 0.58		
II. Wood specific gravity	8.86	0.6
Percent fibers	-1.31	4.9
Regr. constant = 0.30, $F_{3,20}{}^{b}$ = 14.39**, R^2 = 0.58		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

Using the simple correlation information as a guide, multiple regressions were run using a number of independent variable combinations in an effort to explore the possibility of predicting softwood bark strength from either morphological information or some other parameter. None of the measured parameters were well enough correlated with conifer bark strength to warrant use of any of the resulting equations in a predictive capacity. For hardwoods, bark toughness accounted for 85% of the variation encountered, whereas for conifers, bark toughness accounted for only 21% of the variation.

Bark Toughness

Weighted average bark toughness for conifers varies from 0.06 to 0.21. Interestingly, loblolly pine had the lowest and Douglas-fir the highest toughness. Simple correlations run and reported in the wood/bark adhesion section (Table XIII) revealed that conifer toughness was positively correlated with bark specific gravity and percent fibers. Using the simple correlation information as a guide, multiple regressions were run using a number of independent variable combinations in an effort to determine the possibility of predicting bark toughness from either morphological information or some other easily measured parameter. Table XXIII summarizes the multiple regression equation information for the three most promising approaches. Equations I and II indicate that by using bark specific gravity, percent fibers and either weighted average or inner bark strength, bark toughness can be satisfactorily predicted with the resulting equation accounting for 69% of the encountered variation. By using just bark specific gravity and percent fibers (Equation III), 51% of the variation can be accounted for. These results are similar to those obtained for bark toughness in hardwoods and indicate that, as bark specific gravity and the number of fibers increase, the bark toughness can be expected to increase. This latter relationship is particularly useful because of the relative ease with which bark specific gravity and percent fibers can be determined.

Reaction to Hammermilling

Bark removal by a hammermilling-screening procedure and the wood losses which result from using a similar procedure are of particular importance because of the possibility of using such a technique to reduce bark levels in chip fractions having high amounts of bark. As discussed earlier in the section on hardwoods, the basic premise is that bark is weaker than wood and appropriate mechanical action

TABLE XXIII

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION FOR SOFTWOOD BARK TOUGHNESS

	Independent Variables	Partial Regression Coefficients	T-test[a]
I.	Bark specific gravity	0.32	3.2
	Percent fibers	0.02	3.4
	Bark strength	0.01	2.8
	Regr. constant = 0.63, $F_{3,14}$[b] = 10.31**, R^2 = 0.69		
II.	Bark specific gravity	0.34	3.5
	Percent fibers	0.02	3.2
	Inner bark strength	0.01	2.8
	Regr. constant = 0.69, $F_{3,14}$[b] = 10.26**, R^2 = 0.69		
III.	Bark specific gravity	0.34	2.9
	Percent fibers	0.02	2.8
	Regr. constant = -0.23, $F_{2,15}$[b] = 7.90**, R^2 = 0.51		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

will result in the reduction of the size of the bark particles and allow removal by screening. It is intended that the hammermilling be carried out under "dry" conditions and, as a result, the fine fractions removed by screening would be valuable as fuel. Wood toughness, as can be seen in Table XVIII, is consistently greater than bark toughness and any mechanical action that can be employed that takes advantage of this toughness difference between wood and bark could be used to upgrade chip quality. Major differences were also observed for most species between the morphology of hammermilled wood and that of hammermilled bark. No attempt has been made to optimize screening procedures to take advantage of these morphological differences. Increased bark removal, over the results recorded, appears possible through appropriate changes in the type of mechanical action used and through improved screening methods. Bark removal for conifer species varied from 23% for white spruce to 44% for balsam fir (Table XVIII). Wood losses varied very little (3-8%) with 16 of the 18 species having a range of 4-6% wood loss. To examine the relationship between bark removal by hammermilling and wood and bark properties, simple and multiple correlations were run on the variables listed in Appendix Table XXXV. This same table provides the simple correlation matrix that developed for the conifers investigated.

Bark removal was positively correlated with percent sclereids (or phellem cells) and negatively correlated with bark strength. Wood loss was positively correlated with percent bark fiber, an apparent anomaly. Multiple regressions were run using the most promising independent variables as determined by the simple correlation matrix. Table XXIV gives the essential data on the most promising prediction equations. Softwood bark removal by hammermilling was best predicted by using the equation $\hat{Y} = 0.32 + 0.29\ X_1 - 1.37\ X_2$, where X_1 is the percent sclereids (or phellem cells) and X_2 is bark strength. This equation accounts for 44% of the variation encountered and is not as useful an equation as is desirable.

Effectiveness of Hammermilling

Effectiveness of hammermilling is defined as the bark removed by hammermilling minus the wood loss due to hammermilling. Because of the relatively small amount of variation in the wood loss figures for conifers, the results obtained were very similar to those obtained and described in the previous section on "Reaction to Hammermilling."

TABLE XXIV

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION
FOR SOFTWOOD BARK REMOVAL BY HAMMERMILLING

Independent Variables	Partial Regression Coefficients	T-test[a]
I. Percent sclereids	0.28	2.0
Bark toughness	-20.93	0.7
Bark strength	-1.15	1.7
Regr. constant = 0.33, $F_{3,14}$[b] = 4.01, R^2 = 0.46		
II. Percent sclereids	0.29	2.2
Bark strength	-1.37	2.4
Regr. constant = 0.32, $F_{2,15}$[b] = 5.87*, R^2 = 0.44		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

Based upon the simple correlations matrix given in Appendix Table XXXV, it can be seen that the effectiveness of hammermilling was positively correlated with the percent sclereids (or phellem cells) and bark removed and negatively correlated with bark toughness and bark strength. Multiple regressions were run using the most promising independent variables and Table XXV presents the essential data on the most useful prediction equations that were obtained.

Softwood "effectiveness of hammermilling" was best predicted by Equation II which reads $\hat{Y} = 0.265 + 0.31\ X_1 - 0.01\ X_2$, where X_1 is the percent sclereids and X_2 is bark strength. This equation accounts for 50% of the variation encountered in the effectiveness of hammermilling data. Similar results were obtained when percent sclereids were used as X_1 and bark toughness as X_2 (Equation III).

TABLE XXV

MULTIPLE REGRESSION PREDICTION EQUATION INFORMATION
FOR SOFTWOOD EFFECTIVENESS OF HAMMERMILLING

Independent Variables	Partial Regression Coefficients	T-test[a]
I. Percent sclereids	0.29	2.4
Bark toughness	-23.22	1.0
Bark strength	-1.10	1.9
Regr. constant = 0.28, $F_{3,14}$[b] = 5.30*, R^2 = 0.53		
II. Percent sclereids	0.31	2.6
Bark strength	-0.01	2.6
Regr. constant = 0.26, $F_{2,15}$[b] = 7.51**, R^2 = 0.50		
III. Percent sclereids	0.29	2.2
Bark toughness	-43.43	1.9
Regr. constant = 0.26, $F_{2,15}$[b] = 5.29*, R^2 = 0.41		

[a]Test for significance of regression coefficients; values >1.9 considered significant at 0.95 probability level.
[b]Test of significance of regression, * indicates significance at 0.95 level and ** significance at the 0.99 probability level.

The bottom line on "effectiveness of hammermilling" for conifers is that the presence of sclereids (and/or phellem cells) in the bark improves the chances of the bark breaking up and being removed by screening. The effectiveness of hammermilling is decreased by high toughness and high bark strength. The presence of fibers in conifer bark is also expected to decrease the effectiveness of this procedure, as was the case for hardwoods. However, for the conifer species examined, too few species had bark fibers to develop a meaningful mathematical relationship.

WATER FLOTATION BEHAVIOR

One possible method of segregating wood/bark chip mixtures is by water flotation procedures and, in an effort to give as complete a story as possible on the barks of important pulpwood species, a section on "Water Flotation Behavior" was added to all reports. However, since the start of the project, water quality considerations have diminished the usefulness of this approach. In addition, the wet rejects are less useful as fuel. Therefore, this procedure would have limited application in wood/bark segregation procedures and has probably become one of the least important methods investigated in this report.

Two procedures were used to examine the water flotation behavior of bark and wood chips. One procedure involved measuring the density* (green weight divided by green volume) of simulated chips at a number of different moisture contents. The second technique involved measuring the rate of moisture uptake and sinking of wood and bark chips in what have been designated as "dwell time" studies. See the "Experimental Procedures" section for a complete description of the methods used.

Tables XXVI and XXVII summarize densities at 100% moisture content, approximately fresh condition, for both hardwoods and softwoods. Water segregation is believed to be possible when one fraction has a density of less than one g/cc and the other greater than one g/cc at a specific moisture content. As mentioned in the section on "Specific Gravity of Wood and Bark," specific gravity of the wood and bark is highly correlated with wood and bark density at 100% moisture content.

*The term density is used in this report to indicate the weight of wood and bark samples and is expressed in terms of green weight divided by green volume. This is in contrast to the term specific gravity, which is also an expression of the weight of a sample, but in this case it is in terms of dry weight divided by green volume.

Therefore, the specific gravity of these fractions could be used to predict the flotation characteristics of a species.

TABLE XXVI

WOOD AND BARK DENSITIES AT 100%
MOISTURE CONTENT
HARDWOOD

(green weight/green volume)

Species	Wood	Bark
Quaking aspen	0.79	1.15
Eastern cottonwood	0.84	0.81
Northern black cottonwood	0.63	1.04
Black willow	0.82	0.67
Sugar maple	1.24	1.08
Silver maple	0.91	1.11
Red maple	1.03	1.22
White birch	1.01	1.16
Sycamore	0.98	1.21
Sweetgum	0.84	0.87
Yellow-poplar	0.79	0.82
Black tupelo	0.88	0.85
White ash	1.20	0.95
Green ash	1.18	0.91
Shagbark hickory	1.41	1.23
American beech	1.32	1.43
Red alder	0.77	1.15
Post oak	1.27	1.14
Pin oak	1.30	1.31
Black oak	1.29	1.69
Northern white oak	1.30	1.05
Southern white oak	1.38	1.13
Northern red oak	1.06	1.18
Southern red oak	1.25	1.39

TABLE XXVII

WOOD AND BARK DENSITIES AT 100%
MOISTURE CONTENT
SOFTWOOD

(green weight/green volume)

Species	Wood	Bark
Loblolly pine	0.88	0.57
Slash pine	1.10	0.72
Longleaf pine	1.20	0.90
Shortleaf pine	1.10	0.72
Virginia pine	1.08	1.03
Red pine	0.74	0.62
Eastern white pine	0.63	1.01
Jack pine	0.79	0.83
Lodgepole pine	0.89-0.92	0.74-0.95
Ponderosa pine	0.96	0.62
Balsam fir	0.75	1.07
Western larch	1.43	0.61
White spruce	0.70	0.83
Black spruce	0.84	0.97
Engelmann spruce	0.80	1.14
Douglas-fir	0.82	0.82
Eastern hemlock	0.88	0.87
Western hemlock	0.80	0.85

HARDWOODS

The lack of a consistent specific gravity relationship between bark and wood in hardwoods makes the use of a water flotation procedure for mixed hardwood chips virtually impossible except for a few associated species like red alder and northern black cottonwood, which have similar densities at the same moisture content. Even among the seven oaks investigated, there was a great difference in flotation characteristics. Southern white and southern red oak could be segregated at moisture contents of between 25 and 40%. However, the wood would float for southern red oak while the bark would float for southern white oak. The same situation exists for northern white and red oak. Segregation through water flotation would not be possible at all for post, pin or black oak.

Of the three maples investigated, the only one that could be segregated by water flotation techniques is silver maple (moisture contents of between 40 and 115%). No segregation would be possible for red or sugar maple.

CONIFERS

The lack of major differences in specific gravity between the bark and wood makes segregation through water flotation impossible for many of the conifers. A few that could be separated with no additional preparation include eastern white pine, Engelmann spruce, western larch and longleaf and shortleaf pine.

It does appear that a number of the southern pines could be segregated through water flotation although, again, they differ somewhat in the moisture content at which segregation would occur. Robins (16) obtained optimum segregation of loblolly pine by a steaming and compression debarking pretreatment. He then used the Cartesian diver principle at 60 psig for 45 seconds. With no pretreatment, segregation would occur at moisture contents of 145% or more. Segregation would be possible for slash, longleaf and shortleaf pine at moisture contents of 80% or greater. No segregation through water flotation is possible for Virginia pine.

Water flotation segregation is rather difficult to achieve in the case of Douglas-fir and certain pretreatments appear necessary. In another project (Project 2977) at the Institute, Douglas-fir wood and bark chips were subjected to steam pressure at 15 psi and then floated on water at 22°C. Wood recovery was 75-90% with 4-11% bark contamination.

Another problem encountered when trying to segregate conifer wood and bark chips through water flotation was a pitch glaze on some species like balsam fir and white spruce. This glaze inhibits water uptake of the bark and long time periods are necessary to achieve segregation.

Figures 14 and 15 are examples of how the density-moisture content curves look for a species that could be segregated through water flotation and one that couldn't be segregated. Note the closeness of the curves for the latter species. Precision of the method used to obtain the curves is high. Wood and bark density measurements of 16 pulpwood species (64 samples) resulted in an average standard deviation of the mean of three replications of approximately 0.015 and a coefficient of variation (standard deviation/mean) of 2%. Regression analyses of 32 sets of data resulted in the expected significant (95% level of probability) linear relationship between moisture content and density with most r^2 values (correlation between moisture content and density) ranging from 0.50 to 0.93 (17).

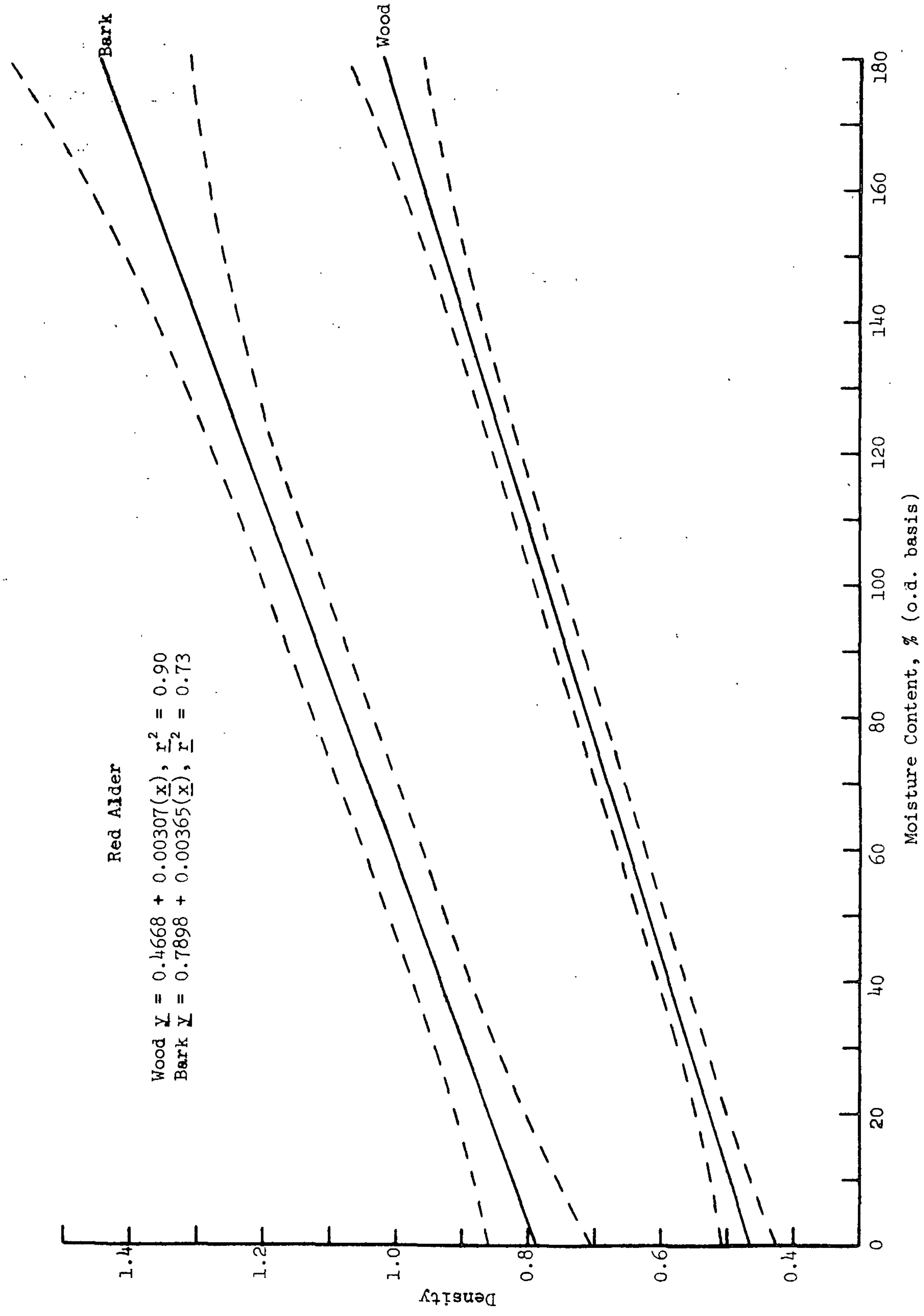

Figure 14. Illustrated is the Relationship Between Basic Density and Moisture Content for Red Alder. The Dashed Lines are Two Standard Deviations Above and Below the Mean

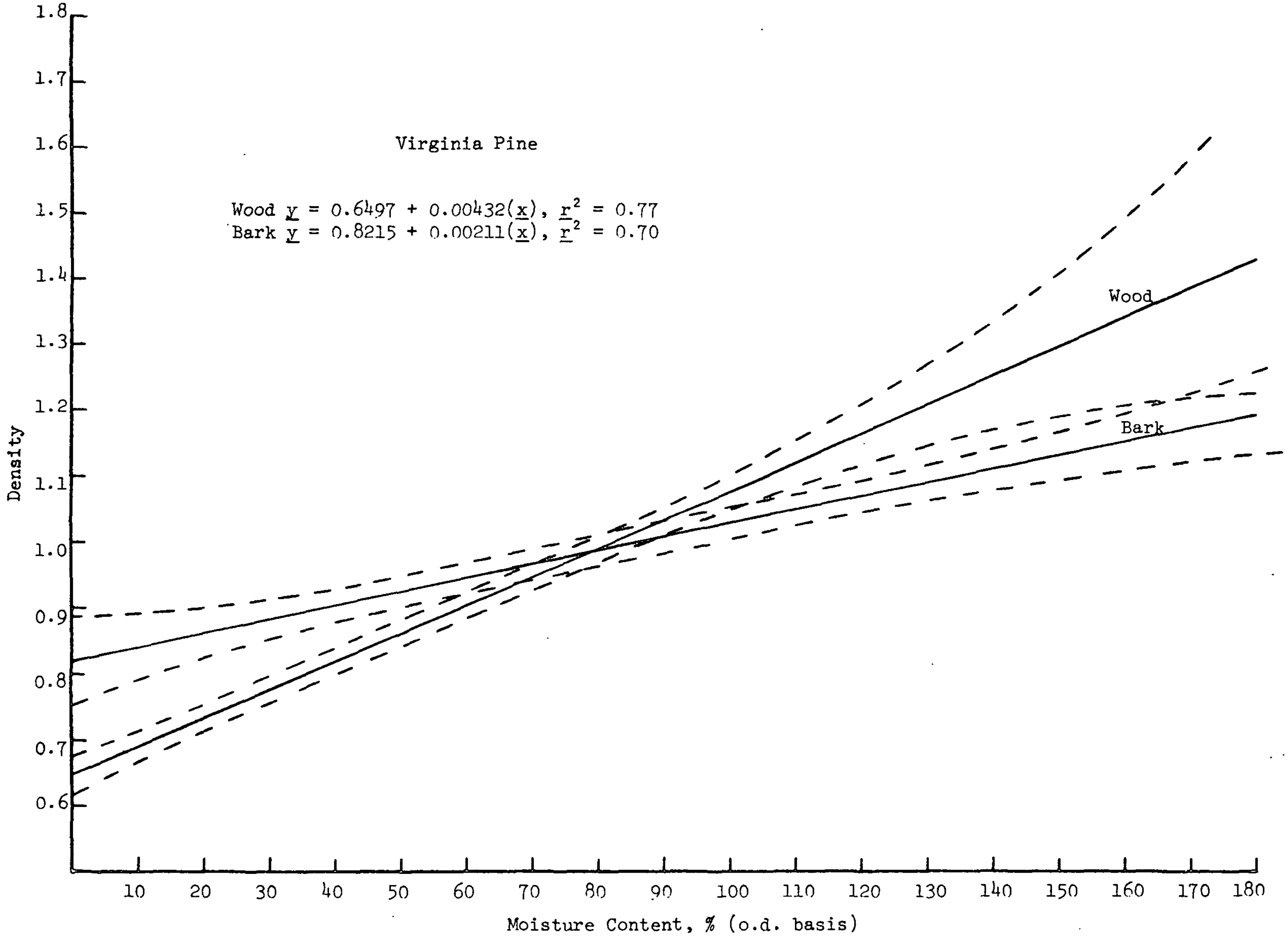

Figure 15. Illustrated is the Relationship Between Basic Density and Moisture Content for Virginia Pine. The Dashed Lines are Two Standard Deviations Above and Below the Mean

BARK FUEL VALUE, ASH, CALCIUM AND SILICA LEVELS

FUEL VALUE

The thrust of the bark characterization research has been influenced by increasing fiber demand, decreasing amounts of forest lands available and present and future energy shortages. A necessarily important aspect of better utilization is the use of bark and wood waste for fuel. For many end products, removal of the bark is necessary and utilization of bark as fuel is a partial solution to disposal of bark waste. Arola (18) estimates that, if 60% of the forest residues being generated were recoverable, it would amount to about 6 billion cubic feet of solid wood annually. If the entire 6 billion cubic feet were used as fuel to generate steam, the gross potential heat content would be about 1,700 trillion Btu. One individual cited a one-third drop in fuel use with a direct-fired wood waste system (19).

In the preceding sections of the report, the relationships between specific gravity, wood/bark adhesion, bark strength, etc., have been examined. Mechanical and water flotation methods of segregation have been considered. Much of this has been examined as a means of cleaning up wood/bark chip mixtures, i.e., removing at least part of the bark. This rejected bark, along with some wood, could be used as fuel, particularly if the material was segregated by a method which kept it dry.

Listed in Table XXVIII are the bark Btu values of the 42 species investigated, both in terms of Btu's per ovendry pound and Btu's per cubic foot. Although values are quite similar when figured on the basis of Btu's per ovendry pound, the relative fuel value of the various species becomes more apparent when the specific gravity of the bark is taken into account and heating value is figured in terms

TABLE XXVIII

BARK FUEL VALUES

Species	Total[a] Sp.Gr.	Weight, lb./ft.^{3}	Btu/lb. o.d. wt.	Btu/ft.^{3}	Literature Values, Btu, lb./ft.^{3b}
Quaking aspen	0.50	31.2	8,712	271,814	318,041 (20), 263,110 (21)
White birch	0.56	34.9	10,332	360,587	371,160 (20), 329,247 (21)
Sugar maple	0.54	33.7	8,426	283,956	299,572 (20), 246,044 (21)
Silver maple	0.57	35.6	8,360	297,616	
Red maple	0.60	37.4	8,293	310,158	
Eastern cottonwood	0.31	19.3	8,422	162,545	
Shagbark hickory	0.72	44.9	8,423	378,193	
Sweetgum	0.42	26.2	7,650	200,430	188,640 (22), 195,190 (21)
Yellow-poplar	0.38	23.7	8,956	212,257	
Black tupelo	0.44	27.5	8,102	222,805	
Sycamore	0.60	37.4	7,978	298,377	
White ash	0.50	31.2	8,453	263,734	
Green ash	0.45	28.1	8,367	235,113	
American beech	0.67	41.9	7,993	334,906	320,116 (20)
Black willow	0.34	21.2	8,137	172,504	151,962 (21)
Red alder	0.58	36.2	8,760	317,112	305,383 (22), 287,681 (21)
N. black cottonwood	0.40	25.0	8,765	219,125	225,000 (22)
Post oak	0.56	34.9	6,773	236,378	
Pin oak	0.71	44.3	8,883	393,517	
Black oak	0.68	42.4	8,340	353,616	
Northern red oak	0.65	40.6	8,896	361,178	320,090 (22)
Southern red oak	0.70	43.7	8,371	365,813	349,250 (22)
Northern white oak	0.58	36.2	7,536	272,803	
Southern white oak	0.56	34.9	8,046	280,805	256,271 (22)
Loblolly pine	0.33	20.6	9,320	191,992	193,640 (23)
Slash pine	0.35	21.8	9,327	203,329	196,244 (21), 204,484 (23)
Shortleaf pine	0.35	21.8	9,310	202,958	208,190 (23)
Longleaf pine	0.45	28.1	9,290	261,049	256,553 (23)
Virginia pine	0.54	33.7	9,170	309,029	283,889 (22)
Douglas-fir	0.41	25.6	9,962	255,027	252,595 (24), 258,560 (22)
Western hemlock	0.45	28.1	9,297	261,246	262,735 (24)
Engelmann spruce	0.51	31.8	8,830	280,794	265,816 (21)
Lodgepole pine	0.38	23.7	9,382	222,353	241,503 (21)
Ponderosa pine	0.35	21.8	9,616	209,629	
Western larch	0.32	20.0	8,825	176,500	164,080 (21)
Balsam fir	0.40	25.0	9,339	233,475	281,190 (20), 221,525 (21)
White spruce	0.39	24.3	8,913	216,586	241,399 (20)
Black spruce	0.42	26.2	9,143	239,547	216,045 (21), 225,582 (20)
Jack pine	0.41	25.6	9,393	240,461	299,155 (20), 224,282 (21)
Red pine	0.27	16.8	9,070	152,376	
Eastern white pine	0.47	29.3	9,647	282,657	
Eastern hemlock	0.43	26.8	9,517	255,056	235,894 (21)

[a]Total includes inner + outer bark.
[b]Literature cited [Chang and Mitchell (21)] values based on airdry samples with an average moisture content of 6% (range 4.8 to 6.7%).

of Btu's per cubic foot. Also given in Table XXVIII are values found in the literature. The literature values have been converted to pounds per cubic foot for comparison with IPC values.

Chang and Mitchell (21) reported that the heating value of hardwood barks was lower than that of softwood barks. They found that the barks of all eight softwood species investigated had values greater than 8500 Btu's per dry pound and nine of twelve hardwoods had lower values. All 18 of the softwoods investigated in this project had values greater than 8500 Btu's per dry pound as did seven of 24 hardwoods. The other hardwoods ranged from 6,773 to 8,453 Btu's per o.d. pound. However, hardwood barks, on the whole, are higher in specific gravity than softwoods and, when this is taken into account by calculating the values on a cubic foot basis, the fuel value of hardwood barks is generally greater than that of softwood barks.

Chang and Mitchell (21) also state that heat of combustion appears to be influenced by the amount of ash and the alcohol-benzene extractives, with higher levels of ash giving lower heat of combustion values and appreciable amounts of alcohol-benzene extractives giving higher values. Simple correlations were run between Btu's per ovendry pound, % alcohol-benzene extractives and % ash for hardwoods, softwoods and all 42 species together. Table XXIX summarizes the results. There was a significant negative correlation between Btu's per o.d. lb. and % ash and the correlation was highly significant for hardwoods and the combination of all the species investigated. The positive correlation between extractives and Btu's was highly significant for hardwoods and all species together but was not significant for softwoods. These results agree with those obtained by Chang and Mitchell with the exception of the lack of correlation between Btu's per o.d. lb. and % extractives for the softwoods. In addition, when all species were combined, there was a significant negative correlation between ash and extractives which was not evident when hardwoods and softwoods were run separately.

TABLE XXIX

SUMMARY OF CORRELATION COEFFICIENTS BETWEEN FUEL VALUE, ASH AND EXTRACTIVES[a]

Material	Btu's/o.d. lb. vs. Ash, %	Btu's/o.d. lb. vs. Extractives, %	Ash, % vs. Extractives, %
Hardwoods	-0.836**	0.518**	-0.337
Softwoods	-0.532*	0.074	0.440
Combination	-0.895**	0.444**	-0.308*

[a]Values between 0.40 and 0.52 are significant at the 5% level (*) of probability while values greater than 0.52 are significant at the 1% level (**) of probability for hardwoods. For softwoods, the values are 0.47 to 0.59 (5% level) and greater than 0.59 (1% level). For the combination, the values are 0.30 to 0.39 (5% level) and greater than 0.39 (1% level).

As a further check on these relationships, multiple regressions were also run. However, they were not any more useful than the simple correlations in establishing the relationship between Btu's per o.d. lb., % ash and % extractives. For most of the species investigated, the percent ash can be used to predict Btu's per o.d. lb. This would probably also apply to many species not investigated in this project. However, the multiple regressions were useful in picking out those species that did not fit the relationship between Btu's, extractives and ash very well. They were sugar and silver maple, white birch, white ash, Douglas-fir, Engelmann spruce, western larch and eastern white pine.

Fuel value is extremely sensitive to moisture content. Green wood of most species has about 60% of the heat value of well air-dried wood. For instance, a pound of oven-dried red oak wood with a calorific value of 8600 Btu's yields about 5700 Btu's when air dried and about 3400 Btu's when green (25). According to McGovern (26), bark, when green, has a net heating value that is one-quarter to one-fifth that of coal, natural gas or oil. Figure 16, taken from data supplied by Cunningham and De Vriend (27), shows the drop in usable Btu's at increasing moisture contents.

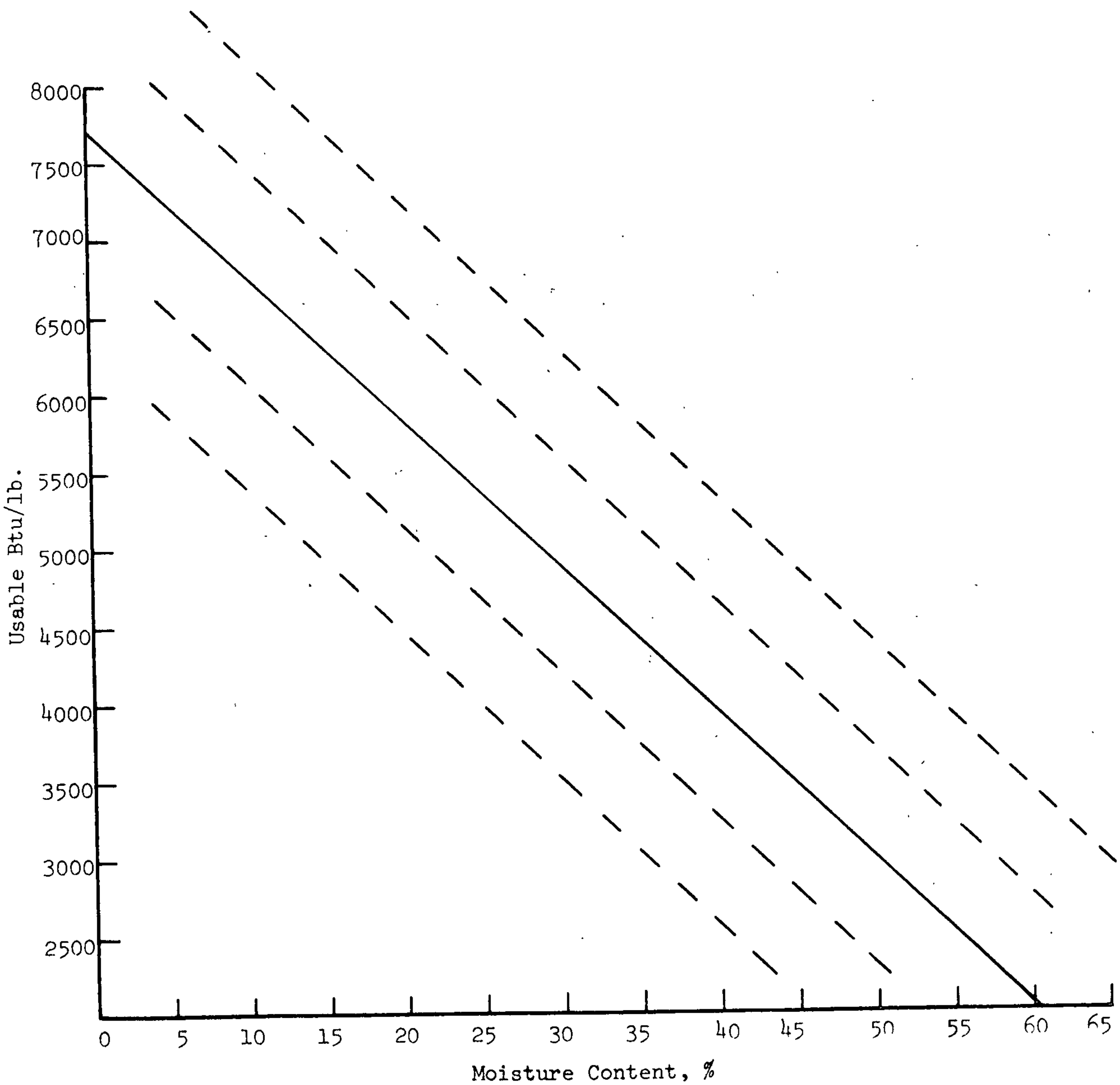

Figure 16. Illustrated is the Effect of Moisture Content on Usable Btu's per Pound

ASH, CALCIUM AND SILICA LEVELS

Listed in Tables XXX and XXXI are percent ash, calcium and silica on an ovendry basis for hardwood and softwood barks, respectively. Ash is the noncombustible part of the bark and needs to be removed, at least in part, after burning. According to Chang and Mitchell (21), a high percentage of ash tends to give lower heat of combustion values. This observation was confirmed by IPC measurements (see preceding section on "Fuel Value"). There was a significant, negative correlation between Btu's per ovendry pound and percent ash for the species examined in this project. Wood has a low ash content, generally less than 1% of dry weight (24). IPC bark ash values ranged from 0.6% for longleaf pine to 17.8% for post oak. All hardwoods had bark ash percentages over 2%, while ten of the 18 softwoods were less than 2%. However, the ash content of bark is lower or comparable to that of most coals, which range from about 5 to 25% ash (28). The ash from a limited sample of southern pine bark was analyzed and found to contain, (as a percent of ovendry weight of bark) about 0.21% Ca, 0.09% Mg, 0.42% N, 0.06% P and 0.32% K (23). When ash is treated with water, the potassium compounds dissolve and marketable potash can be recovered.

Calcium is one of the principal inorganic elements in bark. When bark is pulped, high levels of calcium can be expected to increase recovery system scaling problems. More rapid scaling increases evaporator down time and reduces heat transfer. Lower percentages of calcium in bark are therefore desirable. In 14 eastern Canadian species analyzed by Millikin (20), CaO was found to comprise 48% to 63% of bark ash, compared to approximately 27% for the southern pines. These percentages are a percent of the ash and are, therefore, higher than the percentages given in Tables XXX and XXXI, which are a percent of the ovendry weight of the bark.

Trends were similar for calcium as for ash in the species investigated in this project, with the southern pines being among the lowest (0.2% for loblolly, slash and longleaf pine) and an oak being the highest (5.2% for northern white oak). In general, the softwoods had lower values than the hardwoods, 0.5% vs. 2.4% when comparing the averages for the two groups.

TABLE XXX

PERCENT ASH, CALCIUM AND SILICA IN BARK
HARDWOODS

Ovendry Basis

Species	Ash, %	Literature Values, Ash, %	Calcium, %	Silica, %
Quaking aspen	5.2	2.8 (21), 3.9 (20)	1.9	0.03
White birch	2.4	1.5 (21), 1.7 (20)	0.7	0.06
Sugar maple	8.3	6.3 (21), 5.0 (20)	3.0	0.19
Silver maple	3.6		0.6	0.18
Red maple	5.2		1.5	0.37
Eastern cottonwood	6.2		2.5	0.18
Shagbark hickory	7.3		2.5	0.08
Sweetgum	10.5	5.7 (21)	3.8	1.41
Yellow-poplar	2.8		1.0	0.05
Black tupelo	7.3		2.9	0.11
Sycamore	7.1		3.0	0.06
White ash	4.4		1.6	0.13
Green ash	6.5		1.8	0.12
American beech	10.5	9.4 (29)	3.4	1.1
Black willow	6.3	6.0 (21)	1.8	0.08
Red alder	5.9	3.1 (21), 3.1 (28)	1.4	0.05
N. black cottonwood	5.0		1.1	0.08
Post oak	17.8		5.1	0.02
Pin oak	6.3		2.1	0.1
Black oak	7.5		2.8	0.06
Northern red oak	5.4	5.4 (21)	2.2	0.12
Southern red oak	6.5		2.6	0.14
Northern white oak	12.6	10.7 (21)	5.2	0.29
Southern white oak	8.2	10.7 (21)	3.4	0.42

[a]Ashed at 600°C.

TABLE XXXI

PERCENT ASH, CALCIUM AND SILICA IN BARK
SOFTWOODS

Ovendry Basis

Species	Ash, %	Literature Values, Ash, %	Calcium, %	Silica, %
Loblolly pine	0.8	0.4 (23)	0.2	0.09
Slash pine	0.8	0.6 (21), 0.7 (23)	0.2	0.04
Shortleaf pine	1.6	0.7 (23)	0.4	0.10
Longleaf pine	0.6	0.7 (23)	0.2	0.004
Virginia pine	2.2		0.7	0.01
Douglas-fir	1.2		0.3	0.06
Western hemlock	1.7		0.3	0.04
Engelmann spruce	2.6	2.5 (21)	0.8	0.08
Lodgepole pine	2.2	2.0 (21)	0.6	0.16
Ponderosa pine	0.7		0.2	0.16
Western larch	2.4	1.6 (30)	0.6	0.26
Balsam fir	3.4	2.3 (21), 2.6 (20)	1.0	0.10
White spruce	4.2	3.5 (28)	1.2	0.14
Black spruce	3.1	1.8 (20)	0.8	0.10
Jack pine	1.3	1.7 (21), 2.1 (20)	0.3	0.14
Red pine	1.3		0.3	0.03
Eastern white pine	1.2		0.2	0.17
Eastern hemlock	2.0	1.6 (21)	0.5	0.12

[a]Ashed at 600°C.

Insoluble silicates are naturally occurring minerals that are commonly found in soils. They include not only extremely hard and abrasive types of minerals but silicon as an element in clay minerals of soils. Silica (SiO_2) levels are of interest because, in the form of minerals, they represent the principal acid insoluble fraction in bark and, as such, are expected to remain as one possible abrasive contaminant in pulps.

The SiO_2 levels reported in Tables XXX and XXXI are levels from bark samples which have been carefully harvested and transported and represent SiO_2 levels in bark relatively free from contaminating soil minerals. Some measure of silica levels (principally sand) that are added by harvesting and transporting could be obtained by comparing appropriately sampled and analyzed wood and bark samples from company operations with the relatively soil-free silica (SiO_2) levels reported in Tables XXX and XXXI. Again, as with ash and calcium, softwoods are much lower in inherent silica than hardwoods. Averages for the two groups were 0.10% and 0.23%, respectively.

DATA SUMMARY

Given in Tables XXXII and XXXIII are data summaries for both hardwoods and conifers. These tables have been carried through every report, increasing in size as new species were added. They provide a quick method of comparing the basic information compiled for all 42 species (24 hardwoods and 18 conifers). Specific sections should be referred to for a comprehensive discussion of a point of interest. The "Conclusions" section ties the various parts of the report together, giving general trends in bark fiber content, fuel value, extractives, etc., as well as behavior of bark when subjected to mechanical segregation techniques.

TABLE XXXII

WOOD AND BARK CHARACTERISTICS OF HARDWOOD PULP SPECIES

Characteristic	Quaking Aspen	Eastern Cottonwood	Northern Black Cottonwood	Black Willow	Sugar Maple	Silver Maple	Red Maple	White Birch	Sycamore	Sweetgum	Yellow Poplar	Black Tupelo
Specific gravity (o.d. wt./green vol.)												
Wood	0.38	0.38	0.31	0.36	0.59	0.42	0.51	0.49	0.45	0.44	0.39	0.52
Total bark	0.50	0.31	0.40	0.34	0.54	0.57	0.60	0.56	0.60	0.42	0.38	0.40
Inner bark	0.40	0.29	0.38	0.40	0.69	0.51	0.59	0.57	0.60	0.51	0.38	0.37
Outer bark	0.55	0.32	0.42	0.28	0.49	0.61	0.61	0.54	--	0.36	0.42	0.37
Extractives, % (airdry)												
Wood	3.0	1.4	2.3	2.6	1.0	3.5	1.0	4.0	2.2	2.6	3.9	3.0
Bark	15	7.9	20.0	6.9	6	6.6	6.0	17	8.1	10.2	13.8	10.6
Density at 100% moisture (green wt./green vol.)												
Wood	0.79	0.84	0.63	0.82	1.24	0.91	1.03	1.01	0.98	0.84	0.79	0.88
Bark	1.15	0.81	1.04	0.67	1.08	1.11	1.22	1.16	1.21	0.87	0.82	0.85
Pulp yield, % (bark)	33.8	35.4	26.0	40.0	33.9	32.0	32.0	36.3	31.4	34.9	32.3	31.4
Usable bark fiber, %[a]	10	9	12	21	3	6	12	0	0	5	13	1-10
Sclereids remaining, %[a]	1	<0.1	0	0.3	0.2	2.5	0.9	0.7	--	--	0	0
Fiber location[b]	IB	IB	IB	IB-OB	IB	IB	IB	--	--	IB	IB	IB
Sclereid location[b]	IB	--	IB-OB	--	IB	IB	IB	IB	IB	IB	--	IB-OB
Wood/bark adhesion, kg/cm^2												
Growing season	6.4	4.4	--	--	5.8	6.1	--	5.1	--	10.2	--	--
Dormant season	11.4	13.5	18.7	17.6	10.1	14.1	12.4	12.0	14.8[e]	15.3	16.6	13.5
Bark strength, kg/cm^2												
Inner bark	9.0	17.7	13.9	10.4	1.4	3.4	11.3	1.6	6.1	8.1	13.4	9.6
Outer bark	4.9	4.2	7.3	8.7	4.7	--	--	9.8	--	5.2	10.4	10.5
Toughness												
Inner bark	0.22	0.14	0.10	0.32	0.25	0.17	0.41	0.10	0.15	0.20	0.20	0.20
Outer bark	0.10	0.11	0.07	0.12	0.10	0.12	0.18	0.10	--	0.11	0.18	--
Sapwood	0.45	0.38	0.30	0.44	1.20	0.50	0.63	0.68	0.50	0.28	0.23	0.56
Hammermilling[c]												
Bark removed, %	34	18	26	13	29	14	18	38	45	32	23	39
Wood loss, %	5	5	5	4	5	4	4	6	7	7	7	5

Characteristic	White Ash	Green Ash	Shagbark Hickory	American Beech	Red Alder	Post Oak	Pin Oak	Black Oak	Northern White Oak	Southern White Oak	Northern Red Oak	Southern Red Oak
Specific gravity (o.d. wt./green vol.)												
Wood	0.57	0.56	0.65	0.60	0.37	0.64	0.61	0.57	0.64	0.67	0.56	0.60
Total bark	0.48	0.45	0.72	0.67	0.58	0.56	0.71	0.68	0.58	0.56	0.65	0.79
Inner bark	0.51	0.49	0.69	0.67	0.55	0.65	0.57	0.69	0.65	0.70	0.53	0.68
Outer bark	0.43	0.35	0.81	--	0.62	0.53	0.74	0.68	0.52	0.44	0.71	0.70
Extractives, % (airdry)												
Wood	4.0	4.0	3.2	1.5	2.1	4.3	4.4	5.0	2.4	4.6	4.5	4.8
Bark	12.6	12.6	14.6	10.6	6.0	8.2	14.9	15.4	7.2	8.6	11	11.6
Density at 100% moisture (green wt./green vol.)												
Wood	1.20	1.18	1.41	1.32	0.77	1.27	1.30	1.29	1.30	1.38	1.06	1.25
Bark	0.95	0.91	1.23	1.43	1.15	1.14	1.31	1.69	1.05	1.13	1.18	1.39
Pulp yield, % (bark)	35.7	38.0	28.3	37.0	27.0	46.2	26.5	31.4	35.4	36.6	28.4	30.7
Usable bark fiber, %[a]	16	13	15	0.25	0	4	2	5	3	3	5	4
Sclereids remaining, %[a]	0	0.8	0	--	0	--	--	--	--	--	0.2	--
Fiber location[b]	IB	IB-OB	IB	IB	--	IB	IB	IB	IB	IB	IB	IB
Sclereid location[b]	--	IB-OB	--	IB-OB	IB	IB-OB	IB-OB	IB-OB	IB-OB	IB-OB	IB	IB-OB
Wood/bark adhesion, kg/cm^2												
Growing season	--	--	3.8	--	--	--	--	--	4.8	--	2.5	5.4
Dormant season	23.8	17.4	30.6	14.0	13.0	12.2	12.9	21.5	7.8	7.2	8.4	8.2
Bark strength, kg/cm^2												
Inner bark	20.0	12.6	25.0	7.4	8.2	6.8	10.5	11.7	4.6	4.7[d]	2.1	3.6
Outer bark	4.2	6.4	72.7	--	5.9	3.4	9.9	9.7	3.2	--	4.6	3.4
Toughness												
Inner bark	0.45	0.36	0.90	0.12[d]	0.10	0.20	0.24	0.29	0.16	0.12	0.13	0.11
Outer bark	0.20	0.22	0.71	--	0.02	0.18	0.14	0.10	0.10	0.09	0.18	0.14
Sapwood	0.68	0.64	1.48	1.02	0.50	0.66	0.64	0.86	0.62	0.98	0.93	0.55
Hammermilling[c]												
Bark removed, %	24	32	11	43	48	47	33	37	37	38	34	46
Wood loss, %	6	5	4	6	8	6	6	7	5	3	10	6

[a]Usable bark fiber and sclereids remaining are the fibers and sclereids retained on the 60- and 100-mesh screens. The percentage given is the yield based on whole bark samples.
[b]Major proportion located in either the inner bark (IB) or outer bark (OB).
[c]Based upon simulated hammermilling followed by screening, using the on 14-mesh screen to remove bark and recover usable fiber from fines.
[d]Test performed on total bark.
[e]Sample failed in tensile.

TABLE XXXIII

WOOD AND BARK CHARACTERISTICS OF SOFTWOOD PULPWOOD SPECIES

Characteristic	Loblolly Pine	Slash Pine	Longleaf Pine	Shortleaf Pine	Virginia Pine	Red Pine	Eastern White Pine	Jack Pine	Lodgepole Pine	Ponderosa Pine	Balsam Fir	Western Larch	White Spruce	Black Spruce	Engelmann Spruce	Douglas-fir	Eastern Hemlock	Western Hemlock
Specific gravity (o.d. wt./green vol.)																		
Wood	0.45	0.54	0.55	0.47	0.50	0.39	0.32	0.39	0.39	0.39	0.34	0.50	0.34	0.40	0.34	0.43	0.40	0.40
Total bark	0.33	0.35	0.45	0.35	0.54	0.27	0.47	0.41	0.38	0.35	0.40	0.33	0.39	0.42	0.51	0.41	0.43	0.45
Inner bark	0.29	0.34	0.25	0.26	0.27	0.20	0.32	--	0.32	0.34	0.32	0.37	--	0.33	0.41	0.42	0.40	0.46
Outer bark	0.34	0.36	0.48	0.35	0.56	0.29	0.53	0.43	0.45	0.35	0.46	0.33	0.43	0.46	0.52	0.40	0.44	0.45
Extractives, % (airdry)																		
Wood	3.0	3.3	4.3	4.1	4.1	3.5	7.4	3.9	3.5	5.3	2.0	1.4	2.2	1.5	2.8	4.0	3.7	1.6
Bark	8.5	8.4	8.8	7.7	8.2	5.8	15.5	15.3	15.7	15.7	19.5	14.4	16.0	14.7	24.4	16.4	25.4	11.7
Density at 100% moisture (green wt./green vol.)																		
Wood	0.88	1.10	1.20	1.10	1.08	0.74	0.63	0.79	0.89-0.92	0.96	0.75	1.43	0.70	0.84	0.80	0.82	0.88	0.80
Bark	0.57	0.72	0.90	0.72	1.03	0.62	1.01	0.83	0.74-0.95	0.62	1.07	0.61	0.83	0.97	1.14	0.82	0.87	0.85
Pulp yield, % (bark)	23.6	23.6	26.4	20.1	23.2	33.0	30.5	18.6	27.4	29.1	26.0	27.8	20.6	26.0	24.4	17.6	35.0	35.8
Usable bark fiber, %[a]	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	5	0	0
Sclereids or phellem cells remaining, %[a]	1	2	<1	<1	<1	<1	<1	<1	<1	1	12	0	1.5	3	3	2	4.5	11
Fiber location[b]	--	--	--	--	--	--	--	--	--	--	--	IB	--	--	--	IB-OB	--	--
Sclereid or phellem cell location[b]	OB	OB	OB	OB	OB	OB	OB	OB	OB	OB	IB	--	IB-OB	IB-OB	OB	IB-OB	IB-OB	IB-OB
Wood/bark adhesion, kg/cm^2																		
Growing season	5.8	3.5	--	--	--	--	--	4.0	2.2	5.0	2.4	1.2	4.4	--	3.4	3.4	--	3.6
Dormant season	5.5	9.1	5.2	8.6	7.2	9.6	7.3	10.7	5.6	9.6	9.0	4.4	10.3	18.1	12.5	8.0	14.3	8.2
Bark strength, kg/cm^2																		
Inner bark	3.7	6.4	--	7.4	4.6	--	5.6	2.3	--	4.6	1.7	4.5	--	10.6	--	5.8	5.9	6.0
Outer bark	3.2	5.2	5.8	2.7	4.0	5.6	5.3	2.3	2.4	4.9	1.4	4.4	7.4	7.6	4.2	3.0	5.8	--
Toughness																		
Inner bark	0.10	0.06	0.21	0.16	0.30	0.16	0.20	--	0.10	0.10	0.06	0.12	--	0.22	0.24	0.34	0.16	0.12
Outer bark	0.06	0.09	0.10	0.10	0.16	0.12	0.14	0.07	0.08	0.08	--	0.10	0.16	0.10	0.16	0.03	0.10	0.10
Sapwood	0.54	0.54	0.89	0.94	0.61	0.60	0.36	0.34	0.28	0.26	0.42	0.28	0.34	0.45	0.26	0.58	0.60	0.28
Hammermilling[c]																		
Bark removed, %	34	36	35	29	31	26	29	26	31	26	44	26	23	26	25	28	25	24
Wood loss, %	6	5	6	4	4	5	4	5	4	4	6	6	4	6	4	4	5	3

[a]Usable bark fiber and sclereids or phellem cells remaining are the fibers and sclereids retained on the 60- and 100-mesh screens.
The percentage given is the yield based on whole bark samples.
[b]Major proportion located in either the inner bark (IB) or outer bark (OB).
[c]Based upon simulated hammermilling followed by screening, using the on 14-mesh screen to remove bark and recover usable fiber from fines.

CONCLUSIONS

One objective of this research project has been to better understand the magnitude of the pulp and paper industry's bark problem and, as a result, arrive at a number of alternative solutions that could be applied to specific mill situations, the solution being dependent upon existing equipment, end product requirements and the species mixture employed. Information from the literature has been used extensively in characterizing the pulpwood species investigated and samples from pulpwood-size trees were employed to confirm existing information and supply data where required information was nonexistent.

Bark not only serves a similar function as wood (support, conduction and storage) but serves to protect the tree from insect and disease problems and the inner bark and cambium zone from moisture loss and temperature extremes. Part of the problem associated with the efficient removal and utilization of bark is the large amount of variability that exists between species and between trees of the same species. As a result, a wood/bark segregation technique that appears to be appropriate for one species can often be completely unacceptable for another. Hardwood barks are more variable than conifer barks and contain a variety of morphological structures (fibers, sclereids, parenchyma, sieve tubes, and phellem cells) which influence their behavior and usefulness. Use of morphological characteristics plus the results of a number of physical tests made it possible to predict the pulping, debarking and flotation behavior of both hardwood and conifer pulpwood species.

Bark and wood specific gravity was investigated for 42 pulpwood species and data compared with literature values. Knowledge of the specific gravity of the wood and bark is useful because specific gravity is related to pulp yield and fuel value. Also, differences between wood and bark specific gravity influence the success of water and air flotation procedures. Hardwood bark specific gravity varied from 0.70, 0.71, and 0.72 for southern red oak, pin oak, and shagbark hickory to 0.31 and 0.34 for eastern cottonwood and black willow. Conifer barks varied from 0.33 for loblolly pine to 0.51 for Engelmann spruce. For most species investigated, hardwood barks were higher or similar in specific gravity when compared with conifer barks (Engelmann spruce, Virginia pine, eastern cottonwood, yellow-poplar and black willow are exceptions). Conifer barks were generally similar or lower in specific gravity than the associated sapwood (Engelmann spruce and eastern white pine are exceptions). No consistent relationship was evident between the specific gravity of hardwood bark and that of the wood. For some species the bark was higher and for others the wood had a higher specific gravity. This lack of a consistent relationship made air and water flotation separation procedures of hardwood mixtures virtually impossible. In addition, because of the lack of major differences in specific gravity between the bark and wood of most conifers, it appears that for only a relatively few species would it be possible to separate bark and wood using water and/or air flotation procedures.

Alcohol-benzene extractive levels were measured for 42 pulpwood species. Extractive levels are important because of their influence on pulp yield, chemical requirements, and papermaking pitch problems. Extractive levels in bark did not follow any very consistent pattern with the exception that bark levels were from 3 to 8 times as great as in the wood. Extractive levels in the wood for all species investigated varied from 1.0% for red and sugar maple to 7.4% for eastern white pine. Extractive levels for the bark ranged from 6.0% for red maple and red alder to 25.4% for eastern larch. Most conifer barks have higher levels of extractives than do hardwood barks. Red pine and the southern pines (slash, loblolly, shortleaf, longleaf and Virginia) are the exceptions with extractive levels from only 5.8 to 8.8%. Aspen, northern black cottonwood, white birch, shagbark hickory, pin and black oak are hardwood species with high levels of extractives and Engelmann spruce, balsam fir and eastern hemlock are the three conifers with the highest levels of extractives. Even with these latter species, pitch problems are not expected to be serious unless, as the result of concentrating large amounts of bark from screening procedures, high levels of bark are pulped.

The barks of 42 pulpwood species were examined for the presence of fibers or fiberlike structures. The relative level of fiberlike structures was investigated using a simulated kraft cooking procedure for isolating the fibers and a screening procedure to determine the amount of fiber that had survived cooking and had been retained on a standard 100-mesh screen. Hardwood barks, with the exception of sycamore, white birch, and red alder, have varying levels of fiberlike structures. Black willow, white ash, and shagbark hickory were the species with the greatest amount of usable fiber (15-21%) and all three species had either none or very low levels of sclereids. Eastern cottonwood and yellow-poplar are additional species which had modest levels of fibers and no sclereids.

The bark pulping results for the softwoods was less favorable than for the hardwoods. Most of the species investigated contained little or no fibers. The only exceptions were Douglas-fir with 5% usable fiber and western larch with 1% usable fiber. Evidence in the literature (11-12) indicates that western red-cedar and several other members of the Cupressaceae family also have fiberlike elements in the bark. These results suggest that most conifer barks, when pulped, should not be expected to produce fiber that will contribute to the strength of the paper and board produced. To the contrary, the high amounts of thin-walled cells produced are expected to result in paper machine drainage problems. In addition, softwoods tend to have higher levels of alcohol-benzene extractives and greater numbers of sclereids and/or phellem cells, the latter being potential problems where high yield pulping is involved.

Wood/bark adhesion, shear parallel to the grain, was measured during both the dormant and growing seasons. Little species-to-species variation in growing season wood/bark adhesion was encountered and, as a result, the data provided little information useful in predicting dormant season wood/bark adhesion or debarking difficulties. Growing season wood/bark adhesion failure zones were consistently located in the cambium zone or in the newly-formed nonlignified xylem cells just inside the cambium zone.

Dormant season wood/bark adhesion was measured for 42 pulpwood species and varied greatly from species to species, usually being higher for hardwoods than for conifers. Hardwood dormant season wood/bark adhesion varied from 30.6 kg/cm^2 for shagbark hickory to 7.2 to 7.8 kg/cm^2 for white oak. Conifer wood/bark adhesion varied from 18.1 kg/cm^2 for black spruce to 4.4 kg/cm^2 for western larch. Hardwood dormant season wood/bark adhesion was negatively correlated with the percent sclereids and positively correlated with inner bark strength and the presence of fibers in the inner bark. Use of a stepwise multiple regression procedure made it feasible to predict wood/bark adhesion with a reasonable degree of success using several different independent variable combinations. Use of wood toughness and inner bark strength resulted in an equation that accounted for 72% of the natural variation encountered. Conifer wood/bark adhesion was also related to inner bark strength but the prediction equation developed for conifers accounted for only 49% of the encountered variation.

Bark strength (shear parallel to the grain) was measured in an effort to determine the usefulness of such measurements in the prediction of wood/bark adhesion and reaction to hammermilling and to increase our overall understanding of factors related to the strength characteristics of bark. Hardwood weighted average bark strength varied from 52.2 kg/cm^2 for shagbark hickory to 3.0 kg/cm^2 for sugar maple. Bark strength of the conifers investigated varied less (1.6-8.6 kg/cm^2) and averaged less than the hardwoods studied. Hardwood bark strength was positively correlated with percent fibers and negatively correlated with percent sclereids in the bark. Simple correlations and the multiple regression equation calculations demonstrated that, although bark strength was related to the percent fiber and sclereid level, hardwood bark strength could be best predicted from bark toughness measurements. Conifer weighted average bark strength was positively correlated with wood/bark adhesion and inner bark strength, but was not correlated with any of the morphological factors investigated. Multiple regression calculations resulted in the conclusion that none of the measured parameters were well enough correlated with conifer bark strength to warrant their use in bark strength prediction equations. Most notable was that for conifers and hardwoods inner bark strength was positively correlated with and useful in predicting wood/bark adhesion.

Bark toughness, like bark strength, was measured in an effort to explore how toughness was related to bark morphology and to determine the usefulness of toughness in predicting more complicated properties such as wood/bark adhesion and reaction to hammermilling. Hardwood bark toughness varied from 0.79 for shagbark hickory to 0.09 for red alder. Conifer bark toughness varied from 0.06 for loblolly pine to 0.21 for Douglas-fir. Wood toughness was also measured and of practical interest was the finding that bark toughness was consistently lower than wood toughness, the magnitude of the differences varying from a factor of 2 to 9. Those species where the differences between wood and bark toughness was the smallest were species having large amounts of fiber in the inner bark.

Simple correlations and multiple regression analyses demonstrated that for hardwoods, bark toughness was positively correlated with wood/bark adhesion, percent fibers and bark strength. These calculations also indicated that hardwood bark toughness could be predicted from bark specific gravity, percent fibers and percent sclereids. Similarly, conifer bark toughness could be predicted from bark specific gravity and percent fibers. Hardwood bark toughness, it turned out, was useful in predicting wood/bark adhesion, bark strength and effectiveness of hammermilling. Conifer toughness, however, was less well correlated with wood/bark adhesion and reaction to hammermilling and was a less useful parameter than inner bark strength. The overall practical usefulness of the bark toughness measurements appears to lie in the measured differences between bark and wood and the potential for utilizing these differences in wood/bark segregation procedures.

Reaction to hammermilling was evaluated for the wood and bark of all 42 species. The data was considered to be important because it provided an estimate of the potential of using some type of mechanical action followed by screening to segregate wood/bark mixtures. The basic premise was that bark was weaker than wood and, if appropriate mechanical action could be obtained, much of the bark fraction could be reduced in size and removed by screening. Bark removal, as a result of hammermilling, varied from 11% for shagbark hickory, a species with large amounts of bark fiber, to 48% for red alder, a species having no fiber in the bark. Hardwood bark removal was positively correlated with the percent sclereids and negatively correlated with the percent bark fibers, bark toughness and bark strength. Reaction to hammermilling was best predicted using the percent fibers in the bark ($\underline{r}^2 = 0.58$).

Conifer bark removal varied from 23% for white spruce to 44% for balsam fir. Bark removal was positively correlated with percent sclereids and negatively correlated with bark strength. The presence of sclereids increased the chances of the bark breaking up and the effectiveness of hammermilling was decreased by high bark toughness and high bark strength. Overall, the use of hammermilling continues to look promising, although not as straightforward as originally expected. Major differences exist between wood and bark in toughness and the results indicate the hammermilling procedure employed apparently does not capitalize on these differences as well as anticipated. On the positive side, it appears that some type of mechanical treatment can be developed (chip crushing combined with hammermilling, for example) that would be more effective in bark removal. Interestingly, the type of bark retained is expected to be high in usable fiber and the fine materials removed, if handled by dry techniques, will be a valuable source of energy.

Water flotation was thoroughly investigated as a method of segregating wood and bark chip mixtures. This approach was found to be of limited usefulness. The principal drawbacks were the sensitivity of the system to moisture content, the differences between species in flotation characteristics, the existence of many species in which wood and bark behaved in a similar manner, and the water contamination problems associated with the use of such a procedure.

Energy independence prompted research on the fuel value of bark. The fuel value of 42 species was investigated. The Btu's per oven dry (o.d.) pound of hardwood bark were found to be negatively correlated with bark ash content and positively correlated with the percent alcohol-benzene extractives. The ash and alcohol-benzene extractive correlations did not hold for the 18 conifer species investigated. All 18 conifers had fuel values greater than 8,500 Btu's per o.d. pound, as did 7 of the hardwoods tested. The remaining hardwoods had values that ranged from 6,773 to 8,453 Btu's per o.d. pound. Hardwood barks were on an average higher in specific gravity than conifer barks and, when this was taken into consideration, and fuel values placed on a per cubic foot basis, most hardwoods had higher fuel values than the conifer barks.

Bark ash content, and in particular calcium, is of special interest when whole-tree chips high in bark content are considered for pulping. The ash content of bark was found to be 10 to 15 times greater than that of wood and the use of whole-tree chips is expected to increase pulping chemical recovery system scaling problems. Levels of ash (and calcium) in the barks of conifers are quite consistently less than in hardwood barks. White spruce, yellow-poplar and white birch are exceptions. Calcium levels range from 0.2% in longleaf, slash, loblolly, ponderosa and eastern white pine to 5.2% in northern white oak. <u>These results indicate</u> that extensive use of barky, whole-tree oak chips, particularly the "white" oaks, could greatly increase evaporator scaling, equipment downtime and energy loss due to reduced heat transfer.

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GLOSSARY

Basic density. Green weight divided by green volume.

Cambium. A cylinder, strip, or layer of meristematic cells, which divide to give cells which ultimately form a permanent tissue. The cambium in the stem and root gives rise to xylem and phloem.

Dbh. Diameter breast height (4.5 feet).

Gelatinous fiber. Fiber, the inner wall of which appears in the light microscope to be more or less gelatinous, or jellylike.

Inner bark. Tissues in the cylindrical axis of a tree immediately outside the cambium; includes the region of the secondary phloem from the cambium to the last-formed periderm.

Outer bark. Tissues in the cylindrical axis of a tree immediately outside the inner bark; includes the tissues from the last-formed periderm to the outer surface of the bark; the rhytidome.

Paratracheal. Said of xylem parenchyma in hardwoods which occurs in association with the vessels but nowhere else.

Parenchyma. Tissue consisting of short, relatively thin-walled cells, generally with simple pits; concerned primarily with storage and distribution of carbohydrates.

Periderm. Term applied to the cork cambium (phellogen) and the tissues (phellem and phelloderm) derived from the cork cambium.

Ray. Ribbon-shaped strand of tissue extending in a radial direction across the grain.

Resin canal. An intercellular space, often bordered by secreting cells, containing resin or turpentine.

Rhytidome. A tissue cut off outside a periderm. The cells die leaving a crust made up of alternate layers of cork and dead phloem or cortex; the zone from the innermost periderm outward; the outer bark.

Scalariform. Like a ladder.

Sclereid. See Sclerenchyma.

Sclerenchyma. Mechanical tissue consisting of cells with thick, lignified walls and small lumens. If the cells are elongated, they are called fibers and usually occur in bundles. When the cells are oval or rounded, they are called sclereids. They occur singly or in groups.

Sclerotic. Hard, thick-walled, and often lignified.

Secondary phloem. Inner bark.

Segregation. Removal of either the wood or bark fraction from wood/bark chip mixtures.

Separation. Detachment of bark from wood.

Sieve cell. A characteristic cell of softwood phloem. It translocates food materials synthesized in the plant. Sieve cells are elongated, tapering in shape and lack sieve plates.

Sieve tube element. A characteristic cell of hardwood phloem. It translocates food materials synthesized in the plant. The cells are living, thin-walled, and in longitudinal rows. They are connected by perforations (sieve plates) in their transverse walls, through which pass strands of cytoplasm.

Specific gravity. Ovendry weight divided by green volume unless otherwise specified.

Storied. Arranged in tiers or in echelon, as viewed on a tangential surface of in a tangential section.

Tracheid. Fibrous lignified cell with bordered pits and imperforate ends; in coniferous wood, the tracheids are very long (up to 7+ mm) and are equipped with large, prominent bordered pits on their radial walls; tracheids in hardwoods are shorter fibrous cells (seldom over 1.5 mm), are as long as the vessel segments with which they are associated, and possess small bordered pits.

Tylosis. A balloonlike enlargement of the membrane of a pit in the wall of a vessel or tracheid, and a xylem parenchyma cell lying next to it. It protrudes and blocks the vacity of the wood element.

Uniseriate. Arranged in a single row, series, or layer. Also said of a vascular ray which is one cell wide in cross section.

Vasicentric. Paratracheal; forming a sheath (around vessels).

Vessel. Composite, and hence articulated, tubelike structure found in porous wood, arising through the fusion of the cells in a longitudinal row through the partial or complete disappearance of the cross walls.

Xylary initials. The newly formed vascular tissue which conducts water and mineral salts throughout the plant and provides mechanical support.

Xylem. Wood. The vascular tissue which conducts water and mineral salts throughout the plant and provides mechanical support. It consists of vessels, and/or tracheids, fibers, and some parenchyma.

APPENDIX

TABLE XXXIV

SIMPLE CORRELATIONS BETWEEN HARDWOOD WOOD AND BARK CHARACTERISTICS[a]

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Wood/bark adhesion (1)	1.0	-0.09	-0.05	0.59**	-0.56**	0.40	0.72**	0.78**	0.83**	-0.50*	-0.20	-0.50*
Wood specific gravity (2)		1.0	0.64	-0.29	0.36	0.73**	0.32	0.16	-0.11	0.28	-0.01	0.30
Bark specific gravity (3)			1.0	-0.48*	0.50	0.62**	0.26	0.20	-0.22	0.34	0.22	0.33
% Bark fibers (4)				1.0	-0.60**	-0.03	0.51*	0.45*	0.68**	-0.76**	-0.43*	-0.76**
% Sclereids (5)					1.0	0.20	-0.38	-0.41*	-0.68**	0.41*	0.09	0.42*
Wood toughness (6)						1.0	0.65**	0.63**	0.29	-0.02	-0.25	0.01
Bark toughness (7)							1.0	0.92**	0.68**	-0.50*	-0.33	-0.49*
Bark strength[b] (8)								1.0	0.76**	-0.47*	-0.29	-0.46*
Inner bark strength (9)									1.0	-0.54**	-0.28	-0.53**
Bark removed (10)										1.0	0.53**	0.99**
Wood loss (11)											1.0	0.43*
Effectiveness of hammermilling (12)												1.0

[a]Values from 0.404 to 0.515 significant at 0.95 level of probability (*). Values greater than 0.515 significant at 0.99 level of probability (**).
[b]Average of inner and outer bark values.

TABLE XXXV

SIMPLE CORRELATIONS BETWEEN SOFTWOOD WOOD AND BARK CHARACTERISTICS[a]

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Wood/bark adhesion (1)	1.0	-0.40	0.17	-0.15	-0.16	-0.10	0.23	0.48*	0.50*	-0.36	-0.03	-0.37
Wood specific gravity (2)		1.0	0.12	0.10	0.19	0.58*	-0.11	0.01	0.15	0.28	0.28	0.22
Bark specific gravity (3)			1.0	-0.02	0.10	-0.09	0.51*	0.08	0.00	-0.04	-0.24	0.01
% Bark fibers (4)				1.0	-0.30	0.07	0.49*	-0.01	0.05	-0.08	0.67**	-0.24
% Sclereids (5)					1.0	0.39	-0.20	-0.10	-0.13	0.48*	-0.09	0.53*
Wood toughness (6)						1.0	0.09	0.02	0.32	0.30	0.28	0.25
Bark toughness (7)							1.0	0.46	0.44	-0.43	0.07	-0.47*
Bark strength[b] (8)								1.0	0.86**	-0.50*	-0.03	-0.52*
Inner bark strength (9)									1.0	-0.40	0.02	-0.43
Bark removed (10)										1.0	0.33	0.97**
Wood loss (11)										0.33	1.0	0.11
Effectiveness of hammermilling (12)										0.97**	0.11	1.0

[a]Values from 0.468 to 0.590 significant at 0.95 level of probability (*). Values greater than 0.590 significant at 0.99 level of probability (**).
[b]Average of inner and outer bark values.

TABLE XXXVI

LIST OF SPECIES IN EACH REPORT

Report One	Quaking aspen, white birch, sugar maple, northern red oak
Report Two	Loblolly pine, slash pine, Douglas-fir, western hemlock
Report Three	White spruce, balsam fir, jack pine, eastern cottonwood
Report Four	Northern white oak, southern white oak, southern red oak, sweetgum
Report Five	Lodgepole pine, ponderosa pine, Engelmann spruce, western larch
Report Six	Shortleaf pine, longleaf pine, Virginia pine, red pine
Report Seven	Sycamore, yellow-poplar, black tupelo, white ash
Report Eight	Black spruce, red alder, black cottonwood, silver maple
Report Nine	Shagbark hickory, post oak, pin oak, black oak, American beech
Report Ten	Red maple, black willow, green ash, eastern white pine